MINOS Experiment: Oscillation Results from the First Two Years of Running

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For the MINOS Collaboration

Wine and Cheese Seminar, Fermilab, **19th July 2007**

Outline

- Introduction
- Experiment Overview
- Neutrino Beam and MINOS Detectors
- Beam Neutrino Data in the :
  - Near Detector
  - Far Detector
- Far Detector Oscillation Analysis
- Summary / Outlook

Introduction

- **Neutrinos** were invented in order to solve a **"mystery"** (energy non-conservation in beta decays)…
- Since their birth, they have created even more **mysteries** themselves ...
  - **Solar neutrino "problem"**(ν_e's from the Sun are less than expected)
  - **Atmospheric neutrino "problem"** ("Too few numu problem")
- The "problem" of missing neutrinos can be nicely explained if they posses non-degenerate masses, in which case they can **oscillate** between the different flavors:
  - **3 active (LEP/SLC)**
  - **n sterile (MiniBoone results do not see a signal in the allowed LSND region)**
- **Non zero neutrino masses is one (or the only) of the strongest experimental evidence we have so far for physics beyond the Standard Model!**

3-Flavor Oscillation Formalism

If neutrinos oscillate, then the interaction eigenstates (or weak eigenstates, which is what we observe) can be expressed in terms of the mass eigenstates as follows:

$$\nu_{e(\mu)(\tau)} = \sum_{i=1}^{3} U^{*}_{e(\mu)(\tau)i}\,\nu_i$$

$$\begin{array}{ccccc} & \text{Atmospheric} & \text{Cross Mixing} & \text{Solar} & \\ \mathrm{U}= & \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & -s_{23} \\ 0 & s_{23} & c_{23} \end{bmatrix} & \begin{bmatrix} c_{13} & 0 & -s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ s_{13}e^{-i\delta} & 0 & c_{13} \end{bmatrix} & \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} & \end{array}$$

$$c_{ij} = \cos\theta_{ij}$$

$$s_{ij} = \sin\theta_{ij}$$

$$\begin{array}{cc} \text{Majorana phases} & \begin{bmatrix} e^{ia_1/2} & 0 & 0 \\ 0 & e^{ia_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix} \end{array}$$

0νββ **decays**

2-Flavor Neutrino Mixing

In certain experimental situations only one θ contributes, in which case one can write the oscillation probability as :

$$P = \sin^2 2\theta_{23} \cdot \sin^2\left(\frac{1.267 \cdot \Delta m^2_{23} \cdot L}{E}\right)$$

Physics **Experiment**

Different neutrino experiments , depending on what components of the mixing matrix they want to measure involve:

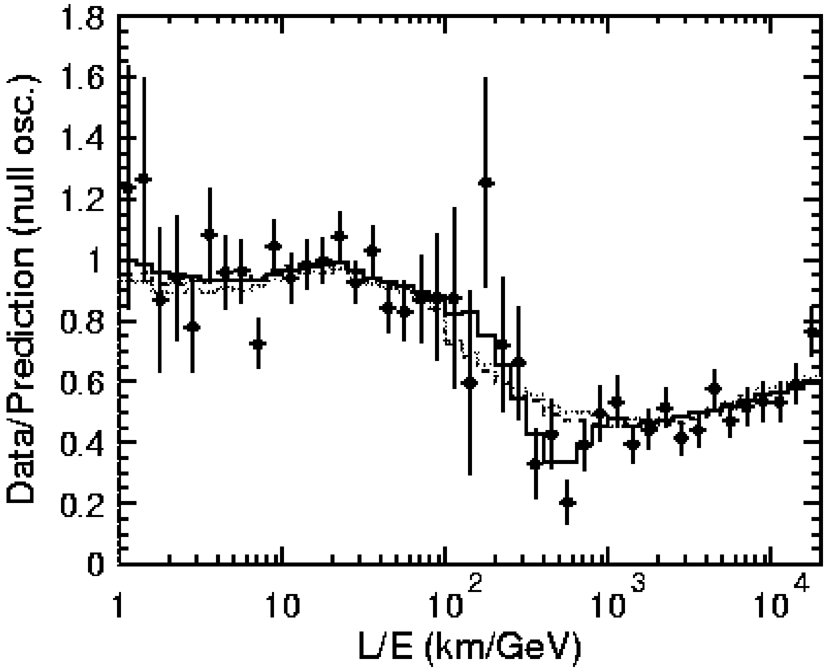
- **Different baselines**
- **Different neutrino energies**
- **Different neutrino flavors**

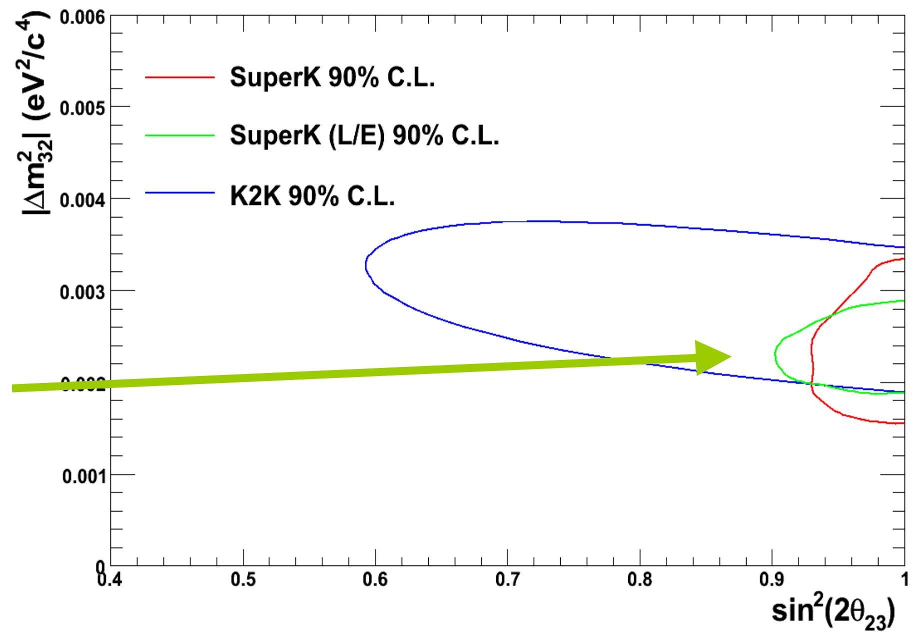
SuperK : Atmospheric neutrinos

- Study ν_μ and ν_e produced in the upper atmosphere.
- Observation : **fewer muon neutrinos than expected**
  : **as many electron neutrinos as expected**

$$\nu_\mu -> \nu_\tau$$

Observed / Expected ν_μ CC interactions





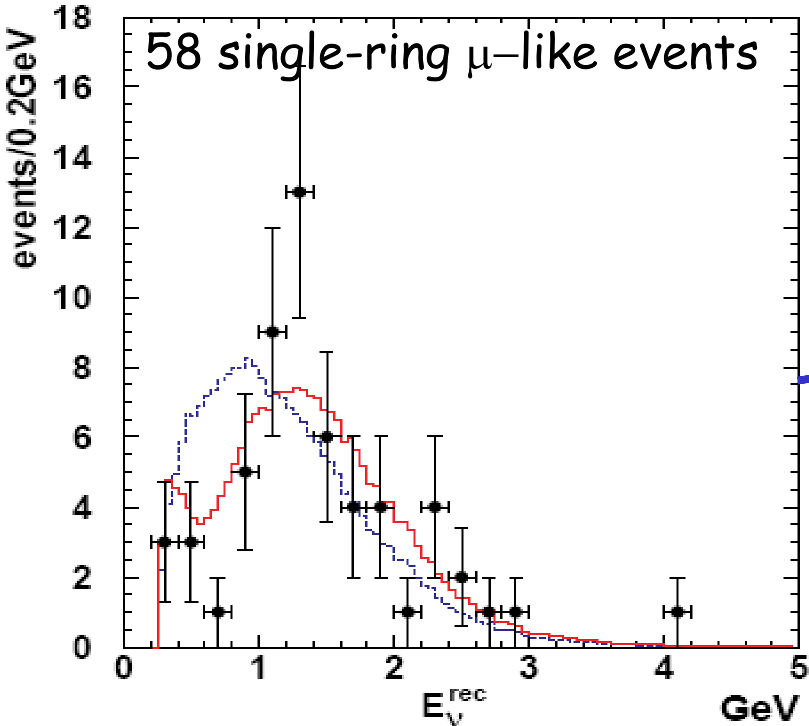
Phys.Rev.Lett. 93:101801,2004

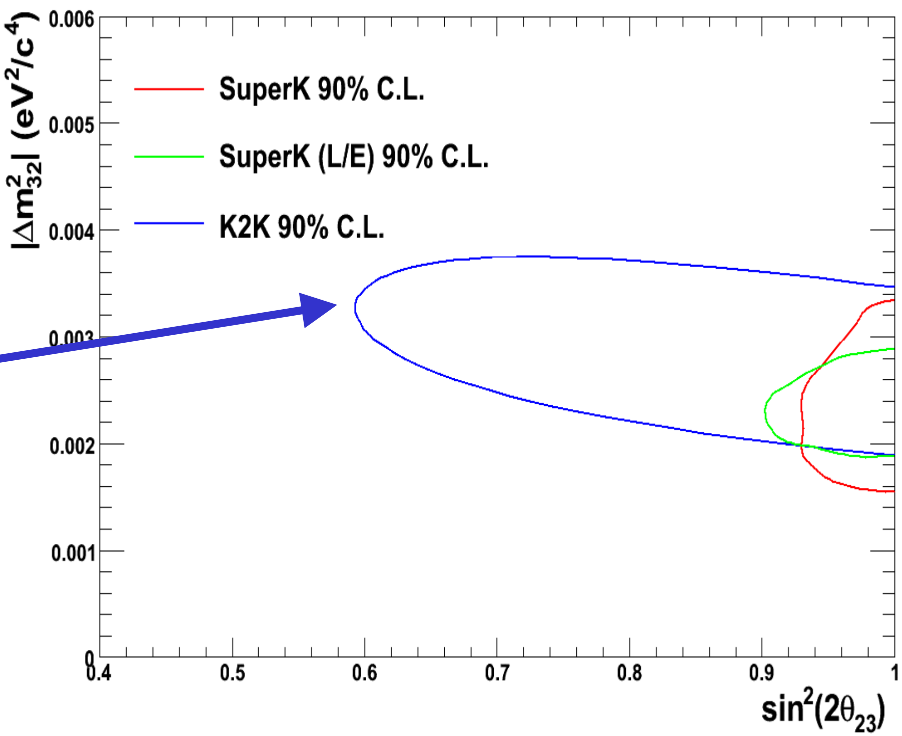
K2K: 1st Long-Baseline Accelerator-based Experiment

Goal was to confirm SK result with accelerator muon neutrinos

112 Observed / 158.1 Expected

L=250Km





Phys.Rev.D 74, 072003,2006

MINOS Collaboration

30 institutions
175 physicists

MINOS Near Detector Surface Building

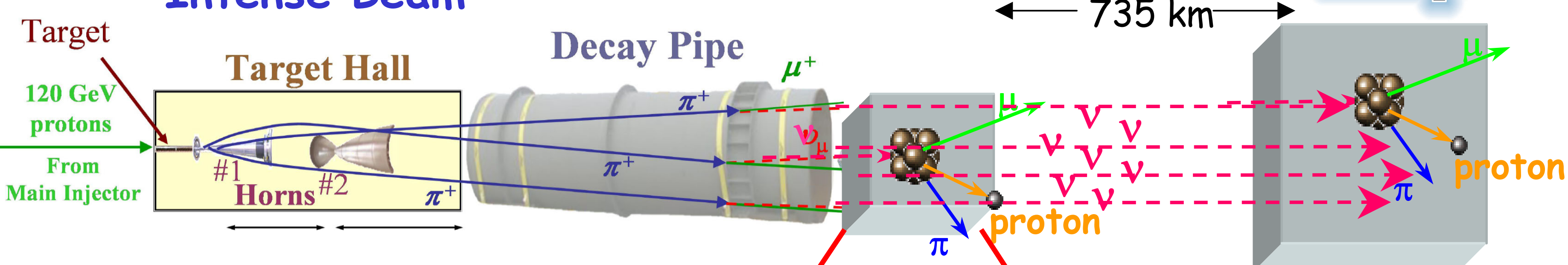
Argonne • Athens • Benedictine • Brookhaven • Caltech • Cambridge • Campinas • Fermilab
College de France • Harvard • IIT • Indiana •
Minnesota-Twin Cities • Minnesota-Duluth • Oxford • Pittsburgh • Rutherford
Sao Paulo • South Carolina • Stanford • Sussex • Texas A&M
Texas-Austin • Tufts • UCL • William & Mary • Wisconsin

MINOS Experiment

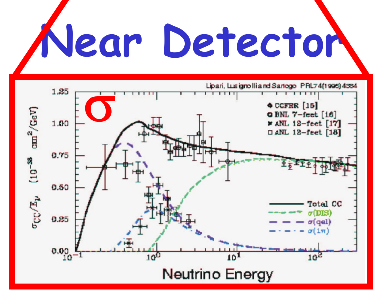
MINOS (Main Injector Neutrino Oscillation Search) is a two detector long baseline ν oscillation experiment.

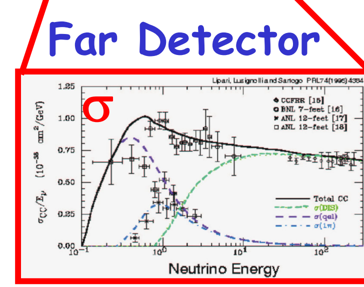
Basic Idea : 2 detectors "identical" in all their important features.

Intense Beam



Cross Section (σ) & Beam Modeling (Φ_ν) uncertainties to high accuracy cancel out between the two Detectors





$$\sigma(E)\cdot\Phi_\nu^{near}(E) \Leftrightarrow \sigma(E)\cdot\Phi_\nu^{far}(E)$$

MINOS Physics Goals

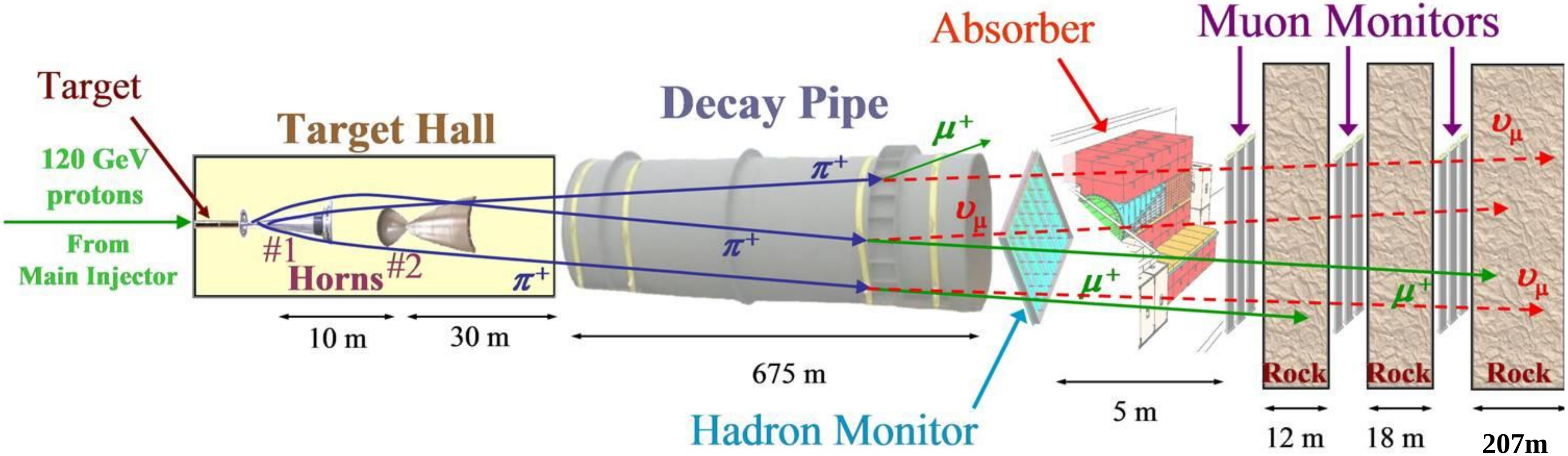
- **Verify $\nu_\mu \rightarrow \nu_\tau$ mixing hypothesis** and make **a precise (<10%)** measurement of the oscillation parameters **Phys. Rev. Lett. 97 (2006) 19180**

- **Search for sub-dominant $\nu_\mu \rightarrow \nu_e$** oscillations (not yet seen at this mass-scale)

- Search for/rule out exotic phenomena:
  - Sterile neutrinos
  - Neutrino decay

- Use magnetized MINOS Far detector to study neutrino and anti-neutrino oscillations (unique capability of MINOS experiment)
  - Test of CPT violation
  - Atmospheric ν oscillations: PRD75,092003(2007),PRD73,072002 (2006)
  - Cosmic rays, hep-ex/0705.3815

NuMI Neutrino Beam



- 120 GeV protons strike the graphite target
- Initial intensity 1.50×10^{13} ppp every 2-4 sec
- Current intensity 2.50×10^{13} ppp every 2.4 sec
- Have also reached 4.05×10^{13} ppp every 2.2 sec

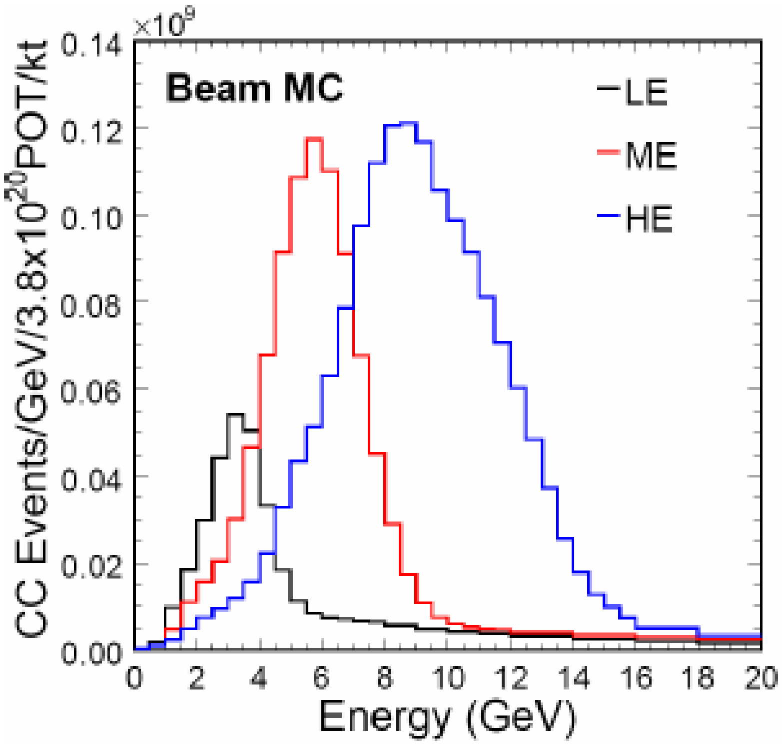
Goal for 2007 is to run stably at ~ 2.5×10^{13} ppp every 2.2 sec

Goal for (2008-9) :

Improve beam Power (by 30-40%)

- From multi-batch slip-stacking to NUMI
- 2.2 sec cycle time during Mixed Mode (stacking)

NuMI: Neutrino Beam configurations



Beam composition

(events in low energy configuration):

98.5% $\nu_\mu + \bar{\nu}_\mu$ **(6.5%** $\bar{\nu}_\mu$**), 1.5%** $\nu_e + \bar{\nu}_e$

- One can obtain different neutrino spectra by moving the target (have taken data already for four different energy configurations).
- These data (ME*,HE*) are used to perform systematic studies in the Near Detector and tune our Monte Carlo.

*** ME = medium energy, HE = high energy, MHE = medium-high resulting from different target positions*

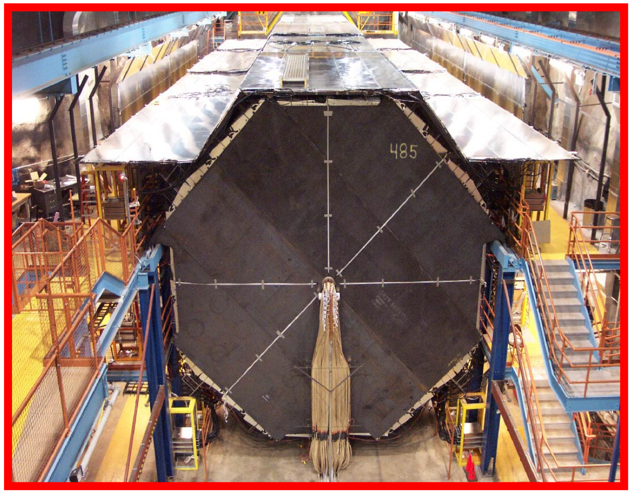
The MINOS Detectors

NEAR

0.98 kt

FAR

5.4kt



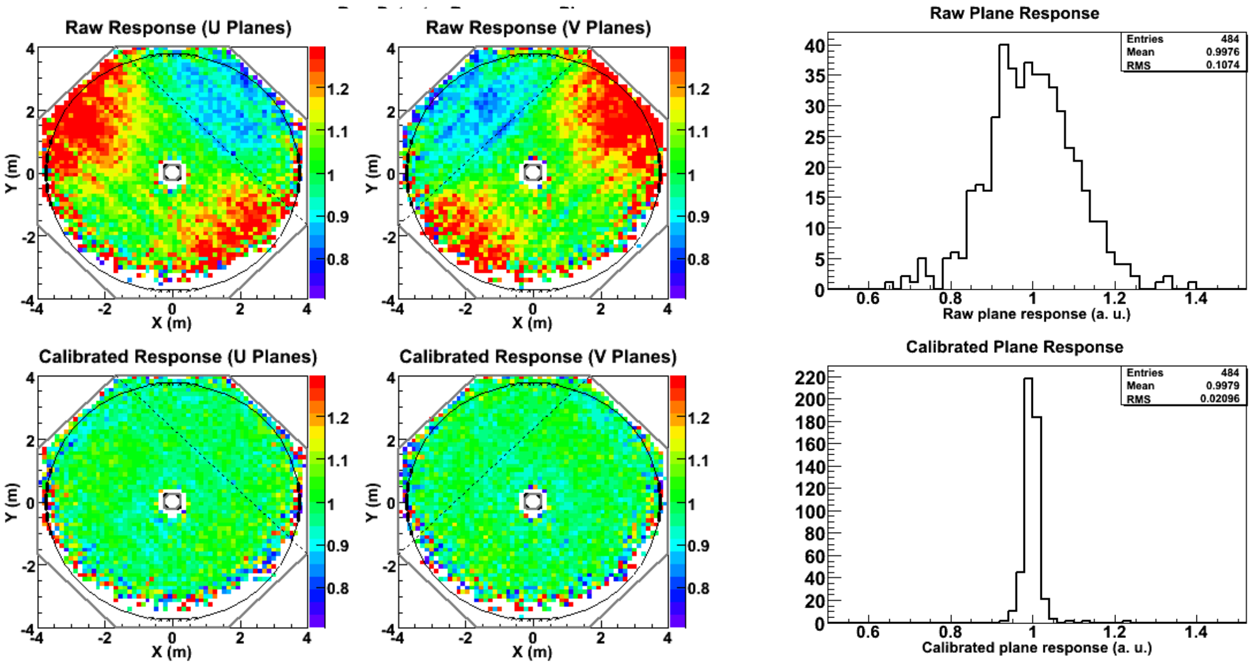
Basic Idea : Two detectors "identical" in all their important features.

Both detectors are tracking calorimeters composed of interleaved planes of steel and scintillator

- 2.54 cm thick steel planes
- 1 cm thick & 4.1 cm wide scintillator strips (read out by WLS fibers)
- 1.3 T toroidal magnetic field.
- Multi-Anode Hamamatsu PMTs (M16 Far & M64 Near)
- Muon momentum resolution ~ 6 % from range (~ 12 % from curvature)

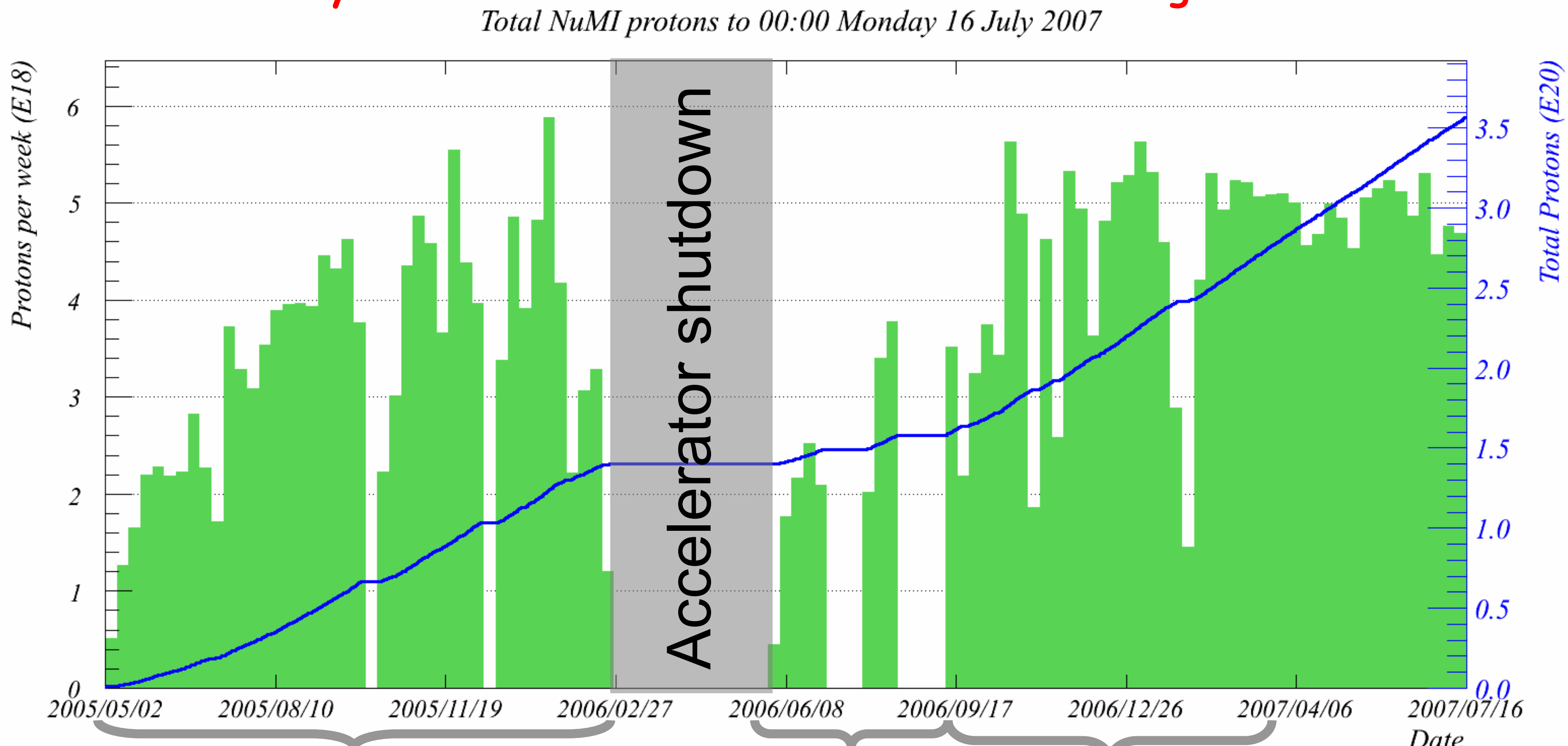
The MINOS Calibration

- Calibration of ND and FD :
  - Calibration detector (overall energy scale)
  - Light Injection system (PMT gain+Linearity)
  - Cosmic ray muons (strip to strip and detector to detector)
- Energy scale calibration:
  - **3.1 % absolute error in ND**
  - **2.3 % absolute error in FD**
  - **3.8 % relative**



MINOS – NUMI Running

Many thanks to our Accelerator Division colleagues!!



Dataset used in the first and current analysis
(1.27x10[20] POT's) Run I

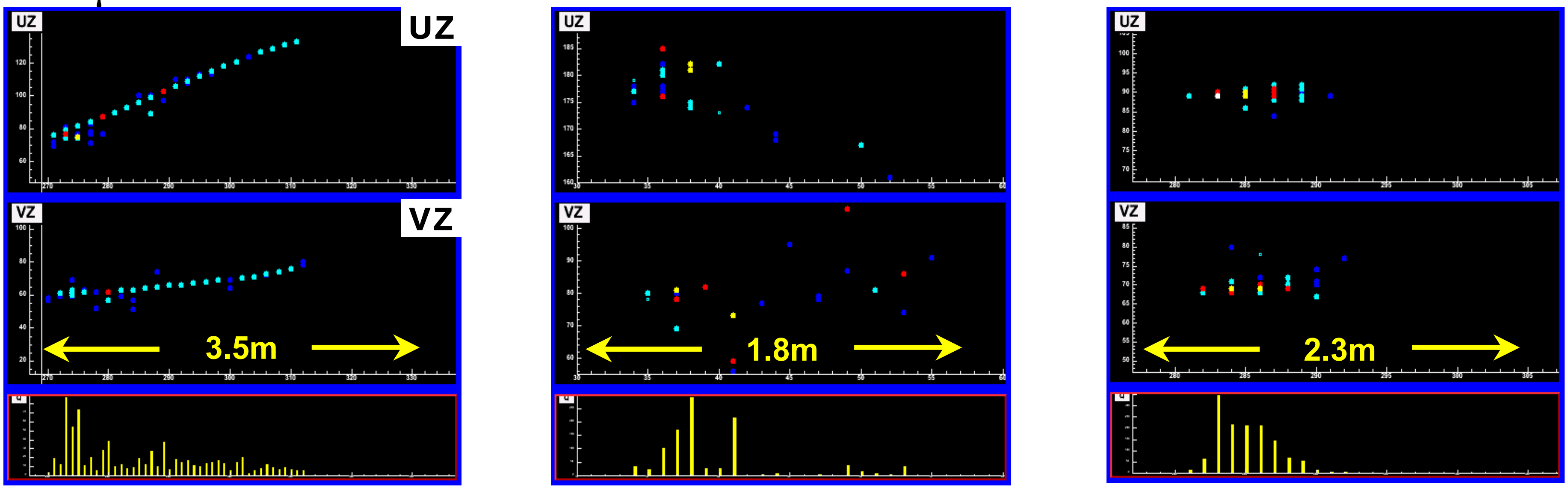
Additional Data Set used in current analysis
(1.23x10[20] POT's) Run IIa

Running in higher energy beam configurations

Neutrino Event topologies

Monte Carlo

ν_μ CC Event | NC Event | ν_e CC Event



Long μ track+ hadronic activity at vertex

Short event, often diffuse

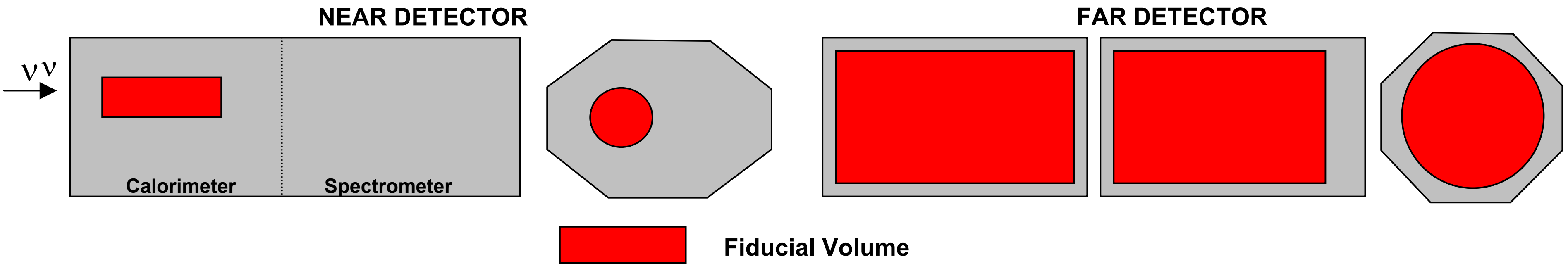
Short, with typical EM shower profile

$$E_\nu = E_{shower} + P_\mu$$

Event Selection Criteria – Near and Far

ν_μ CC-like events are selected in the following way:

1. Event must contain at least one reconstructed track
2. The reconstructed track vertex should be within the fiducial volume
3. The fitted track should have negative charge (selects ν_μ)
4. Cut on likelihood-based Particle ID parameter which is used to separate CC and NC events.



Analysis Changes w.r.t. published (Phys.Rev.Lett.97(2006)19180) Analysis

Reconstruction – Event Selection

Improved track reconstruction :

1) More events satisfy pre-selection track quality related criteria

Improved Event Selection with the use of 2D PDFs (correlations are taken into account) and more Discriminating variables :

2) Increased efficiency for selecting ν_μ CC
3) Increased background rejection (less NC contamination)

Enlarged Far Detector Fiducial Volume and relaxed 30 GeV Energy Cut on Analysis sample:

4) Increased overall neutrino selection efficiency

Analysis Changes w.r.t. published (Phys.Rev.Lett.97(2006)19180) Analysis

Intranuclear Re-scattering - Hadronization & ν Cross Section Modeling

Updated/Improved Models (show better agreement with world's data).

-We determine the relationship between hadronic true and visible energy from the MC. These changes in the MC resulted in a 10% decrease in the visible shower energy in both Near and Far Detector Data (original systematic uncertainty 11%)

**MINERνA experiment will help better understand intranuclear Re-scattering effects and hadronization modeling*

Selecting Charged Current Interactions

Events are selected using a likelihood-based procedure, with six input variables and 2D Probability Density Functions (PDFs) that show discriminating power between True CC and NC interactions:

- **Track Topology Variables**
  - Track Pulse Height Per Plane
  - Number of Track Only Planes
  - Number of Track Planes
  - Goodness of Muon Track Fit
  - Reconstructed Track Charge
- **Event Variables**
  - Reconstructed Kinematics Y distribution (Y = Shower Energy / Neutrino Energy)
- **Relative CC/NC Spectrum and CC/NC Priors**

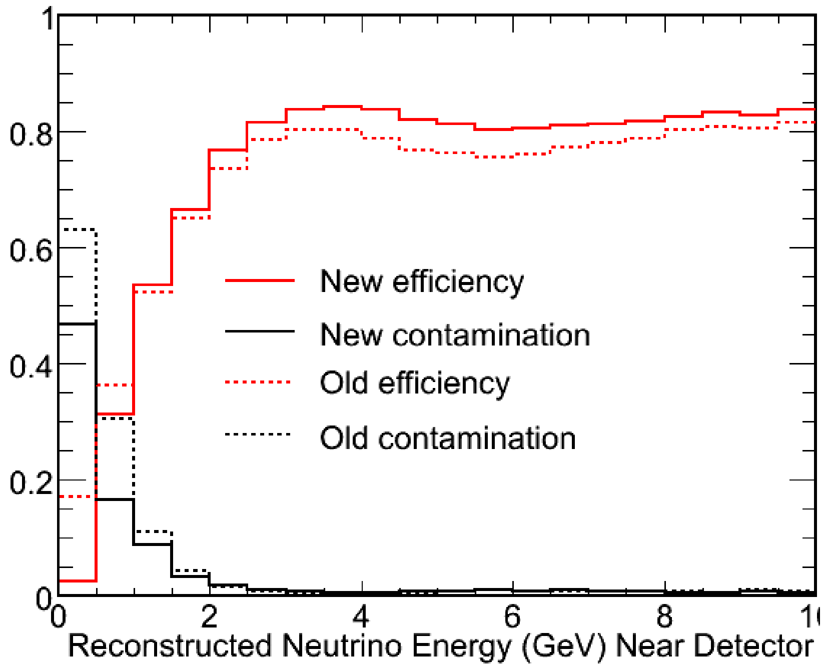
$$P_{CC}(X,Y,Z,\ldots) = P(X|CC)\,P(Y|CC)\,P(Z|CC)\,\ldots\,P(CC)$$

$$P_{NC}(X,Y,Z,\ldots) = P(X|NC)\,P(Y|NC)\,P(Z|NC)\,\ldots\,P(NC)$$

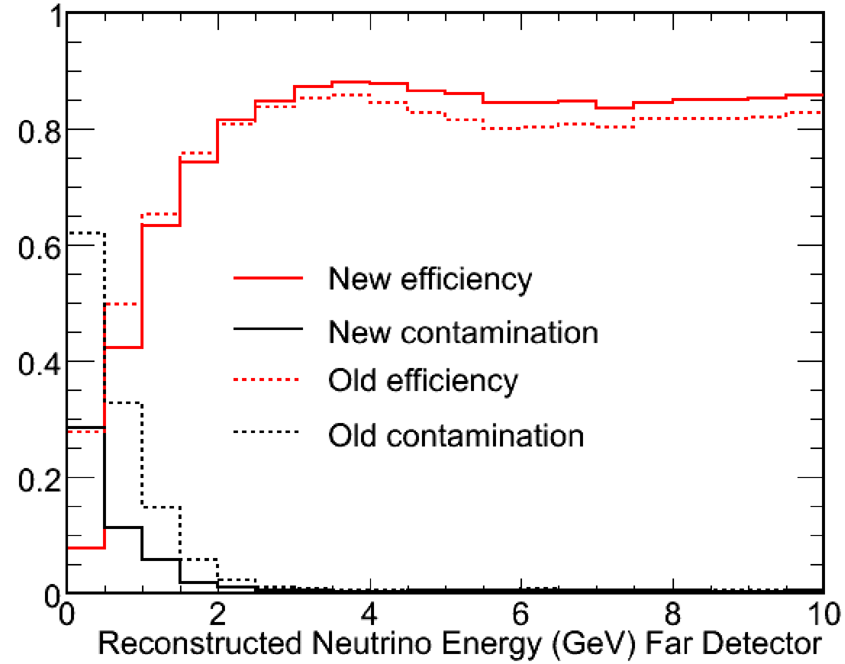
$$\boxed{PID = \frac{P_{CC}}{P_{CC} + P_{NC}}}$$

PID Improvement over old Analysis

NEAR



FAR

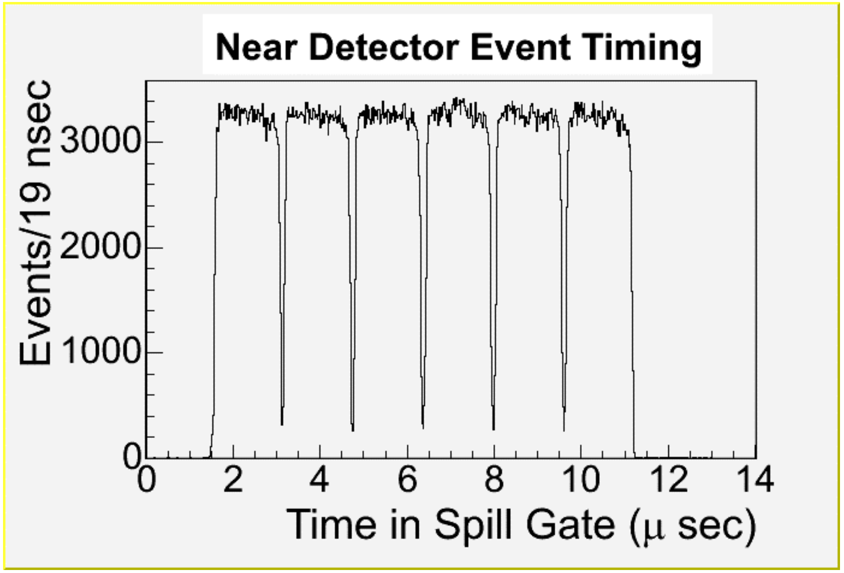


New PID has higher overall efficiency and higher background rejection (less contamination from NC interactions)

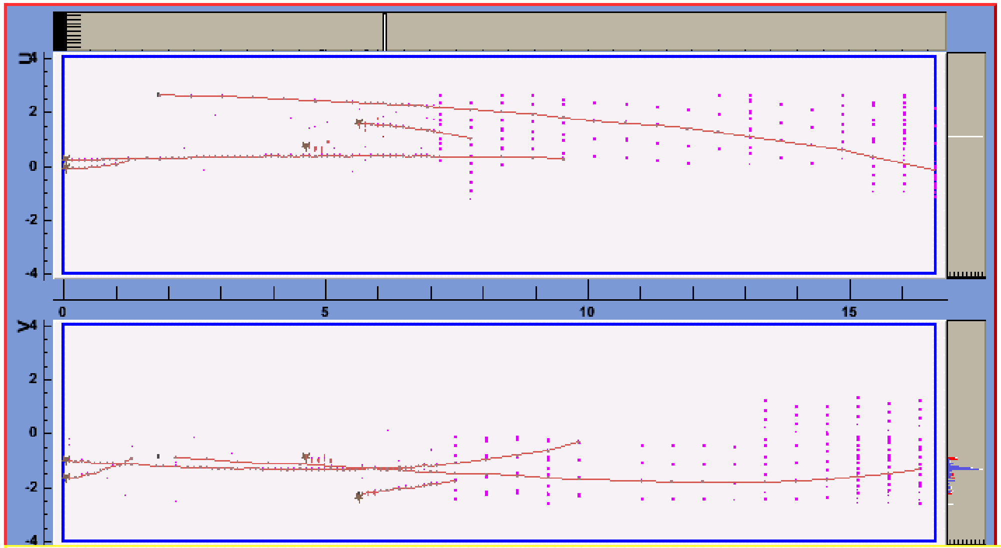
Near detector event reconstruction

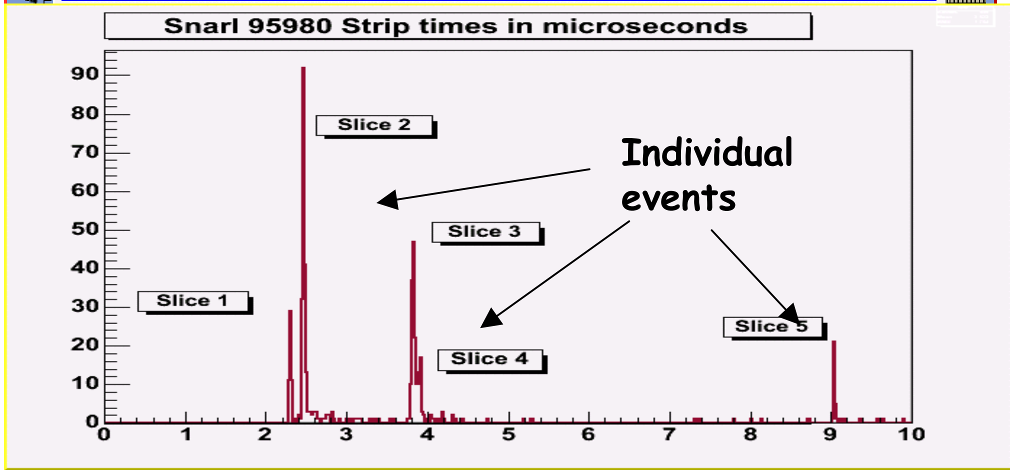
- **High rate** in **Near detector** results in multiple neutrino interactions per MI spill

- Events are separated by topology and timing



One spill in the Near Detector



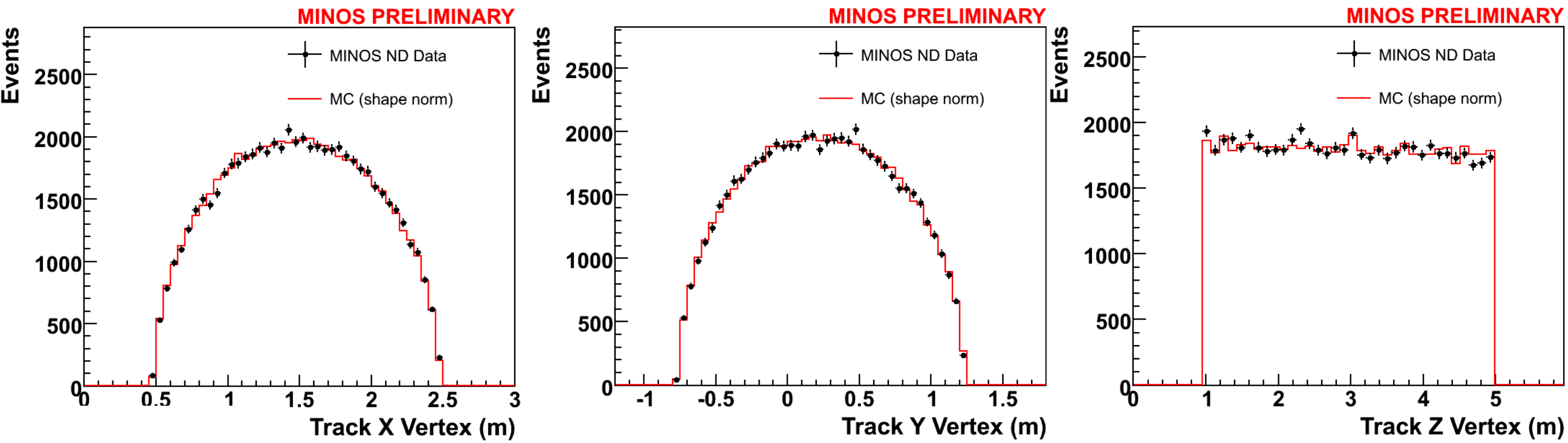


Time (us)

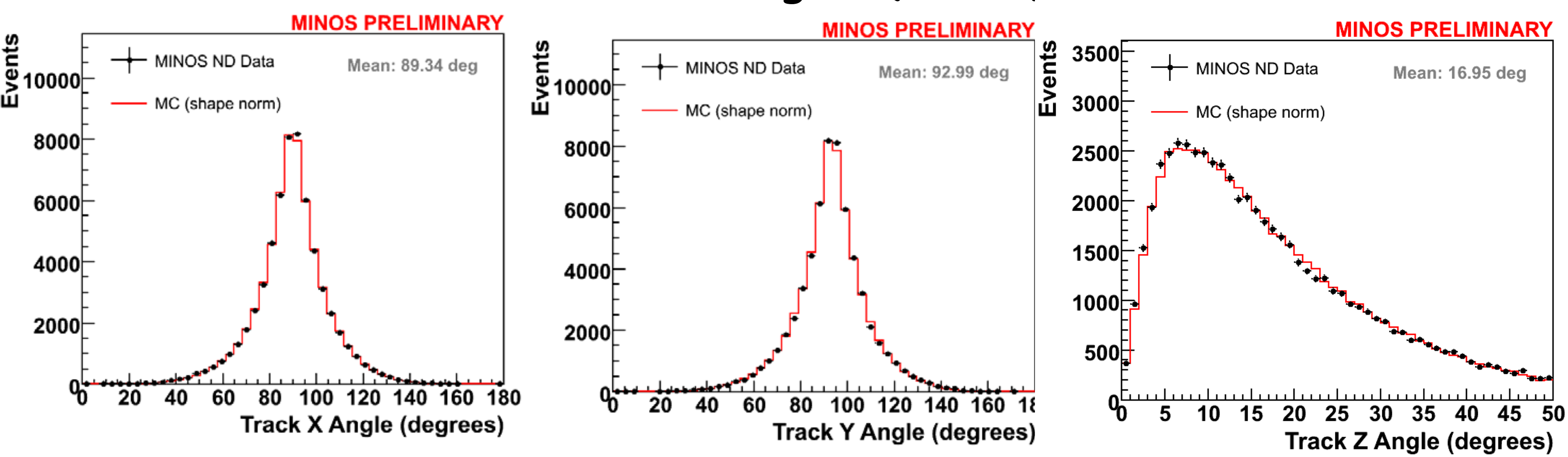
Near Detector : Data/MC

Plots normalized to area

Event Vertices (X Y Z)

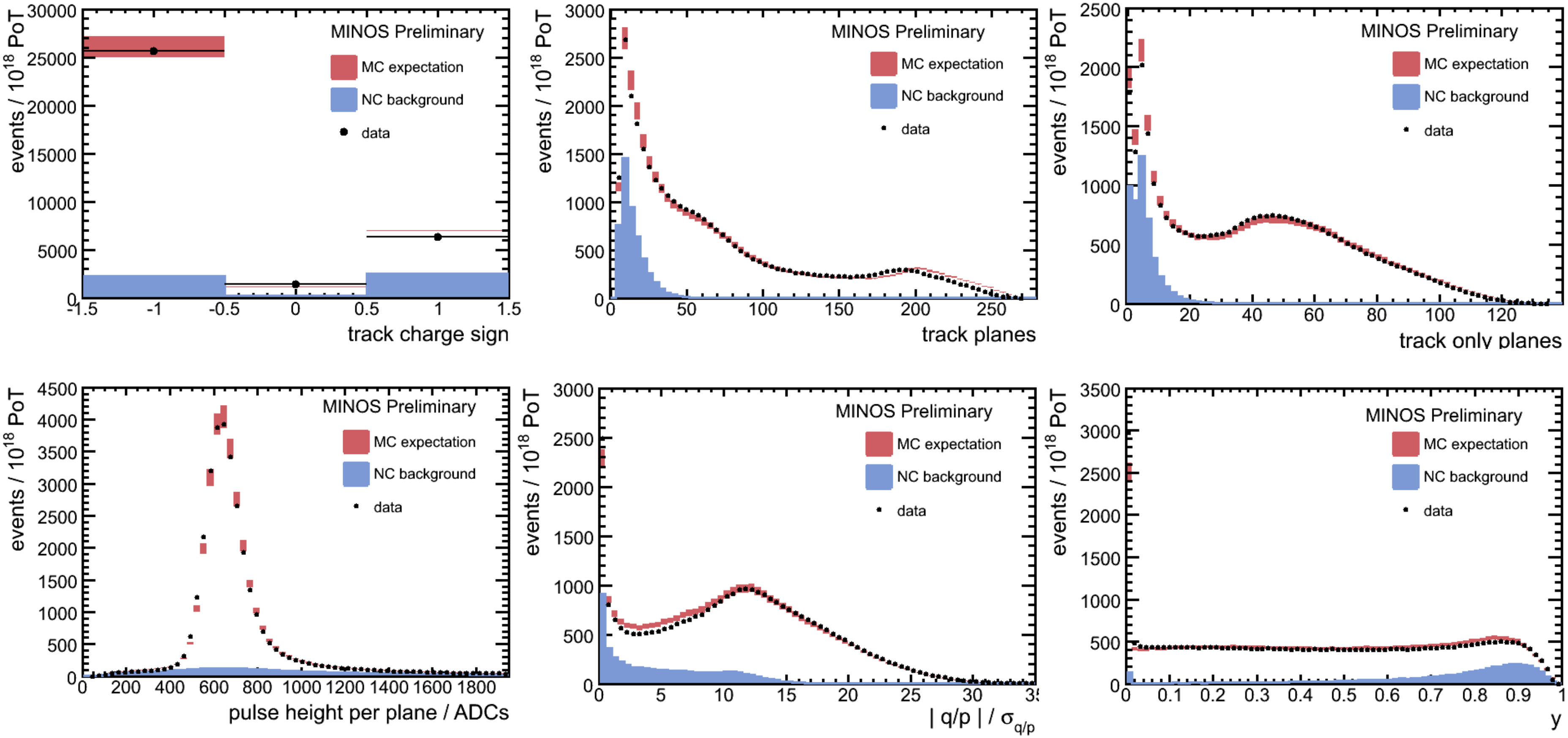


Track Angles (X Y Z)



Low Level ND Quantities agree quite well.

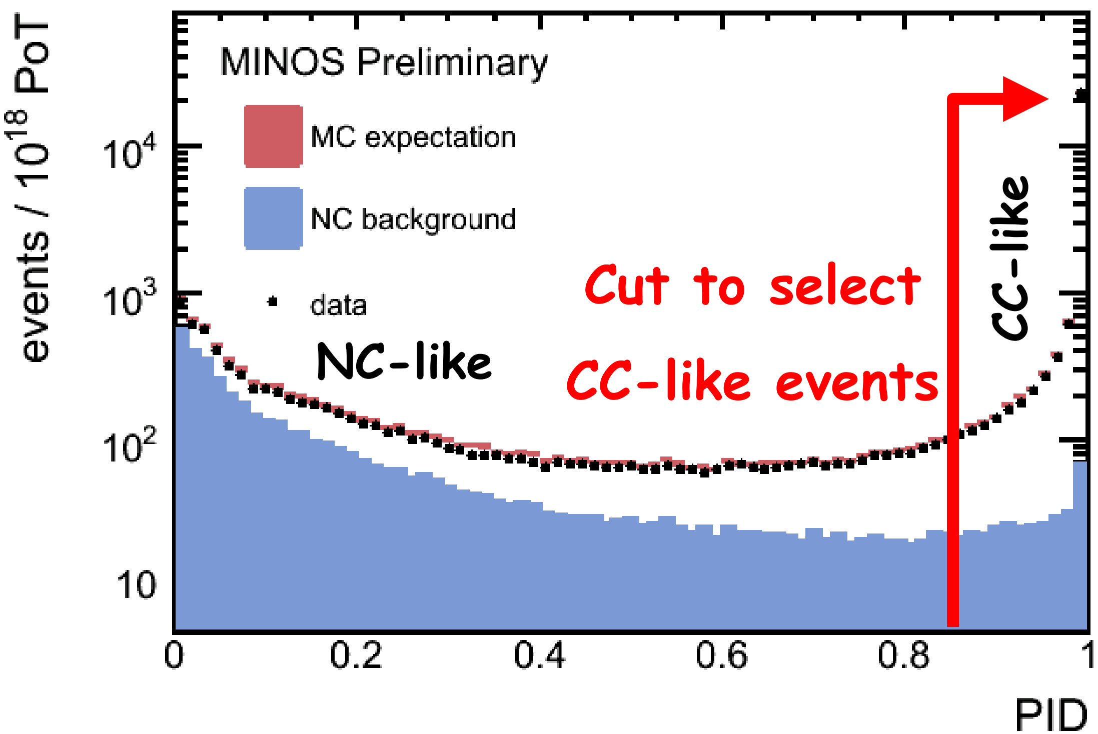
Near Detector : Data/MC
Particle IDentification Input Variables



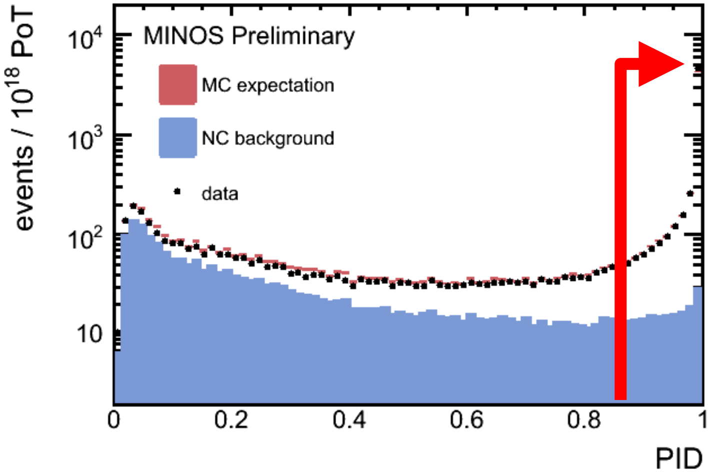
Input Variables used for CC-NC Separation agree well between Data and MC

Near Detector : Data/MC
Particle IDentification Distribution

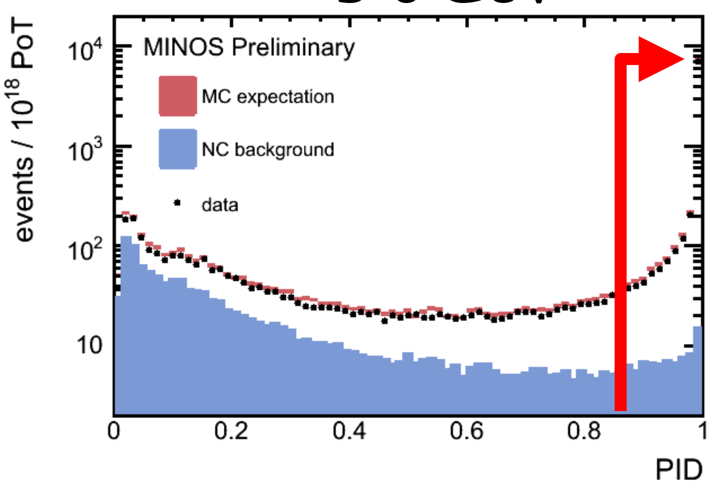
All Energies



0-3 GeV

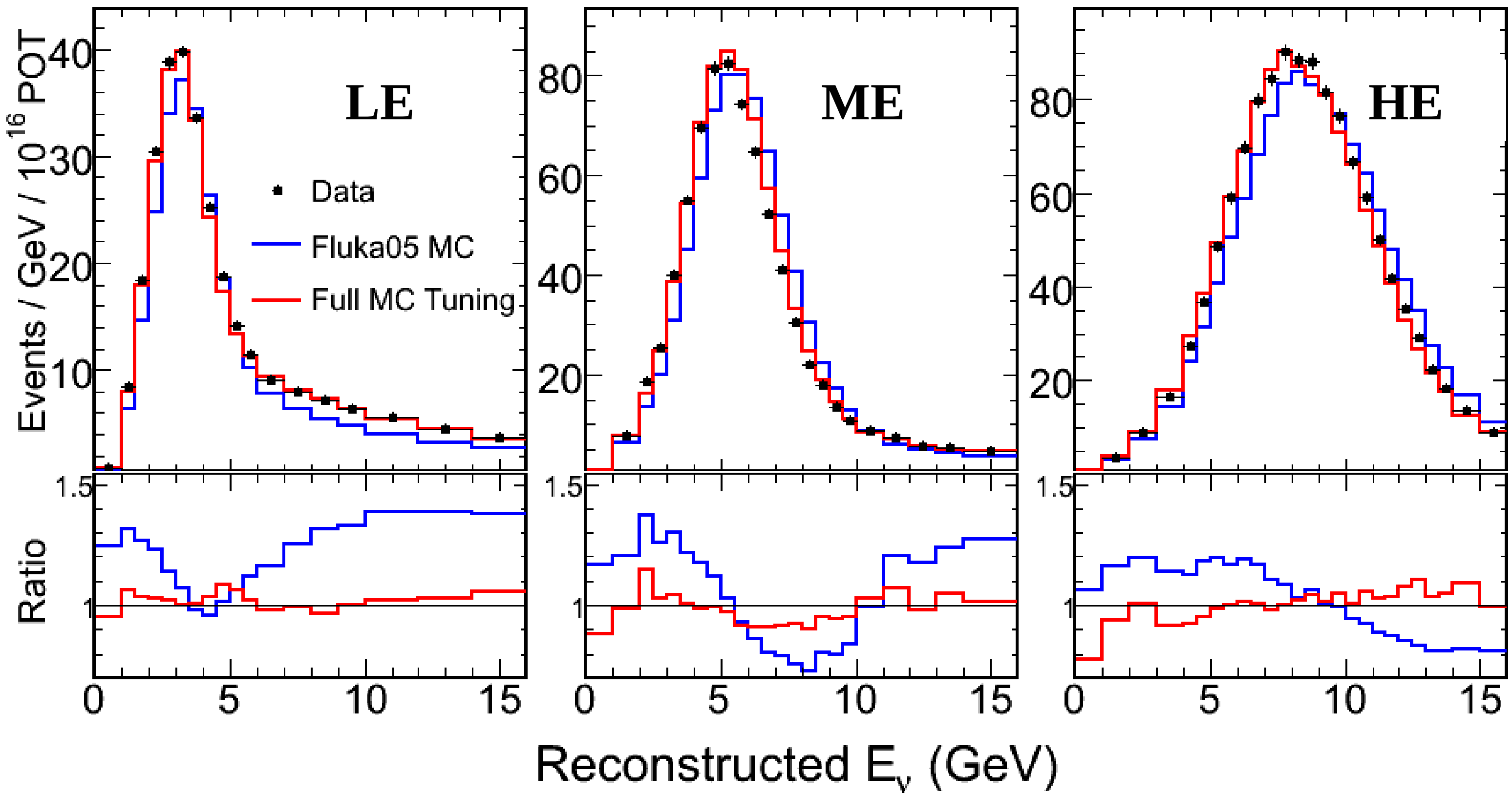


3-6 GeV



Agreement between Data and MC very good, for all neutrino energies.

Near Detector: Data/MC (Hadron Production Tuning)



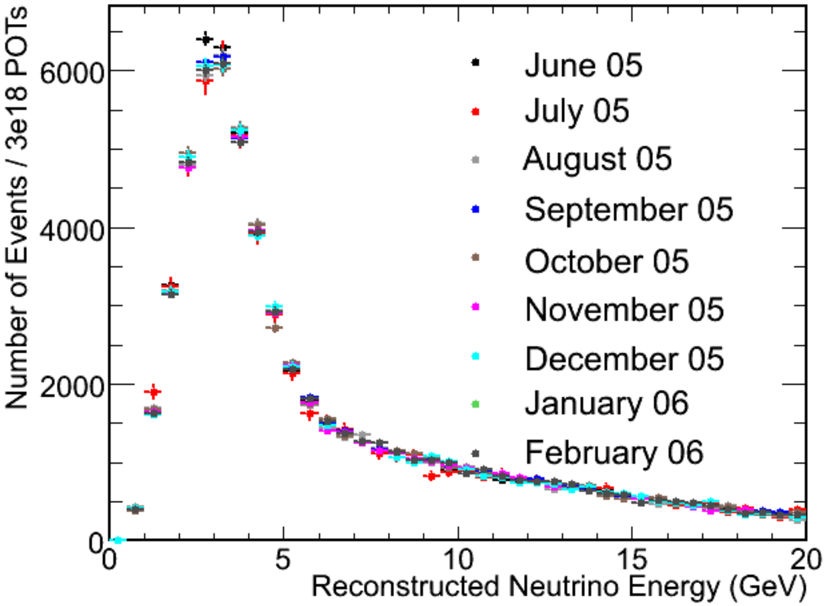
• Disagreement between Data /MC : "Dip" that moves with neutrino energy for different target positions, characteristic signature of beam modeling effect (hadron production)

• MC tuning (on hadron x_F and p_T) improves the agreement between Data and MC.

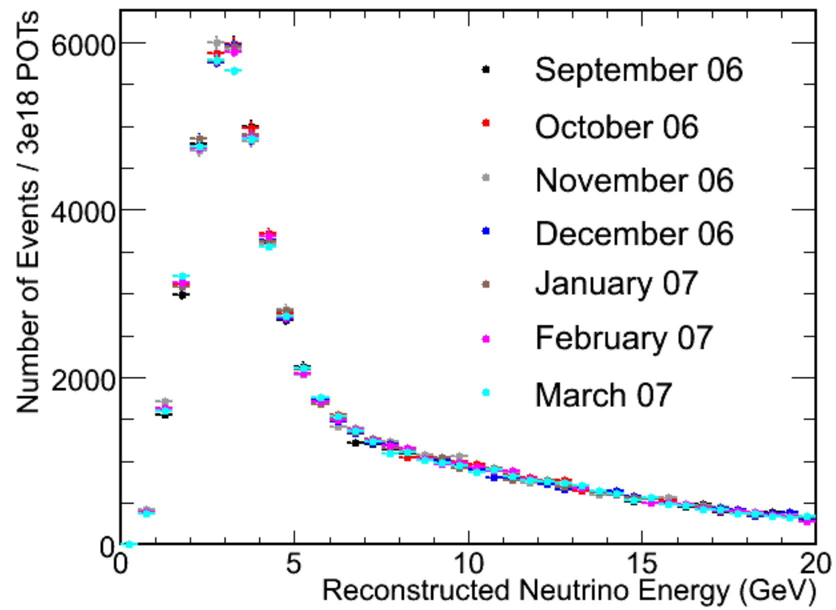
• Results from the MIPP experiment will help us further improve our understanding of the hadron production model.

Near Detector : Data Stability

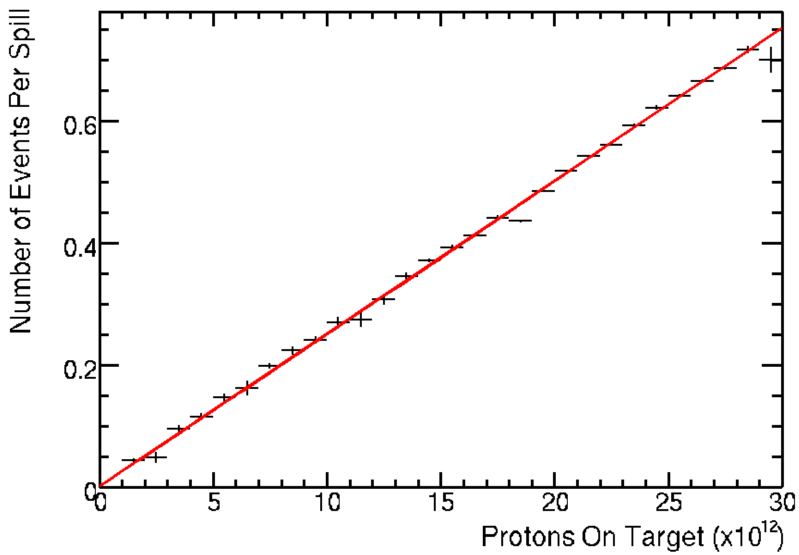
Energy spectrum by Month: Run I



Energy spectrum by Month : Run IIa



- Beam is very stable and there are no significant intensity-dependent biases in event reconstruction.
- Run IIa Data are different (~7% lower at the peak) from RunI Data due to different target position (known identified effect)



Near Detector Data : What did we learn

- The agreement between Data/MC of low level quantities indicates that there are no major detector/reconstruction effects not modeled by our MC.

- The disagreement between Data/MC of the reconstructed neutrino energy spectrum is related with the main uncertainties that we mentioned earlier (hadron production and cross sections modeling).

- We would like to use a Near-Far extrapolation technique as insensitive to these systematics uncertainties as possible.

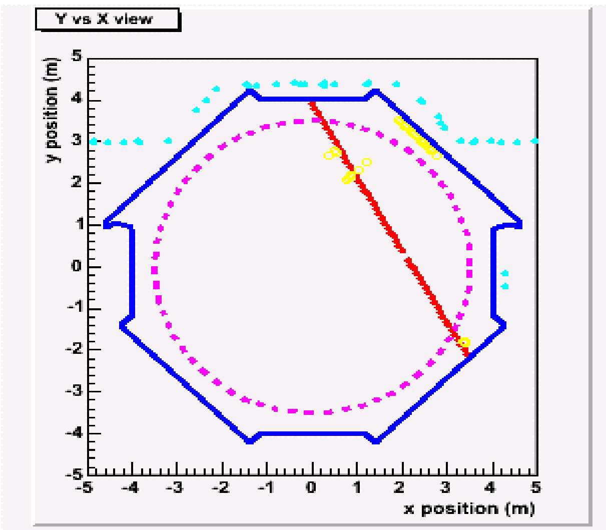
Far Detector Beam Data: Blind Analysis

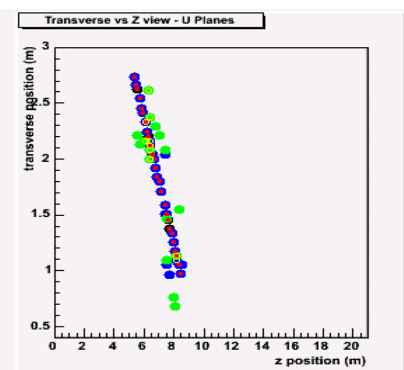
ΘΕΜΙΔΑ

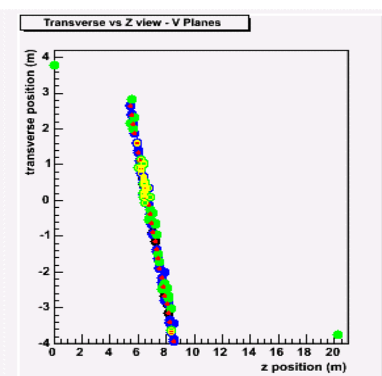
Justice is Blind

- Since May 20th 2005 running in the Low Energy configuration
- Collaboration decided to perform Blind Analysis:
  - Unknown (energy biased) fraction of our Far Detector Data are "open" and we use them to perform data quality checks.
  - Remaining fraction of our Far Detector Data are "hidden" and final analyses will be performed on total sample once Box is opened.
  - Once data quality is assured and cuts and analysis decided on, box is opened
  - ***After Box Opening for the first analysis we re-blinded our data using a different function.***

Far Detector Data : Typical Events







In the Far detector we record events that satisfy either of the following trigger conditions:

4/5 consecutive planes

OR

Sum of ADC >1500 (PH/plane = 800 ADC for muons) or 6 hits in any 4 consecutive plane window

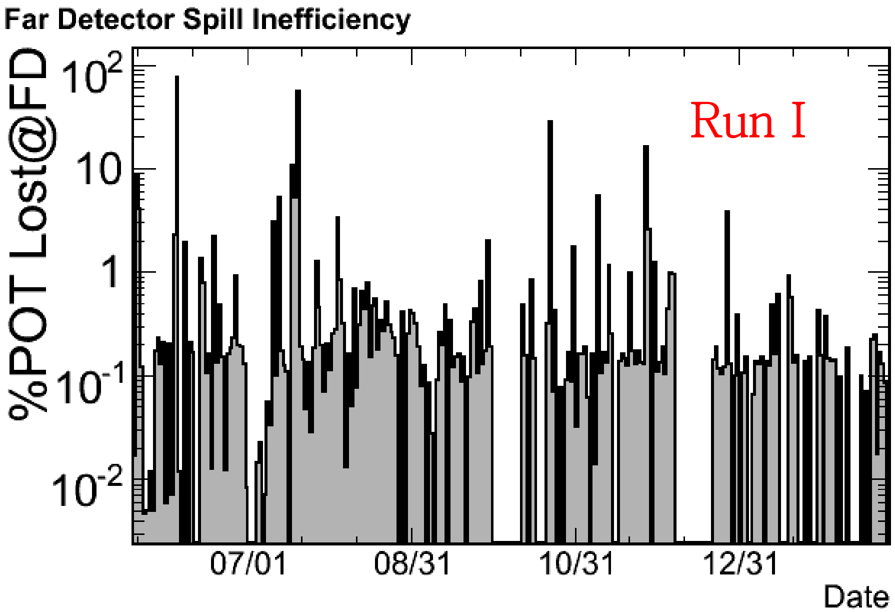
OR

Events within +/-50 usec from a beam spill (GPS "spill time" is send via internet to Far DAQ for triggering)

Also events +/- 50 usec from "fake spill". ("Fake spill" data used for background studies)

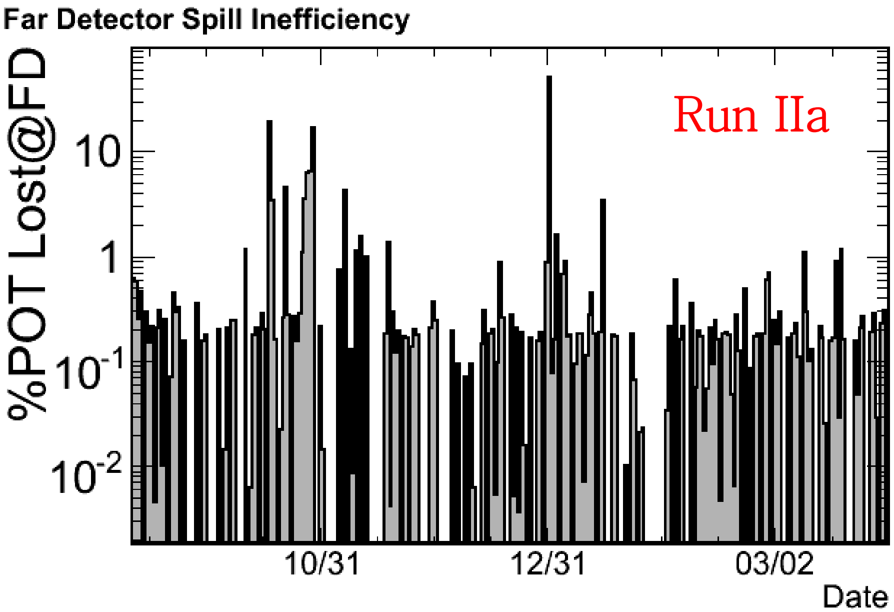
Mostly record cosmic ray muons at a rate of 0.5 Hz .

Far Detector Live Time



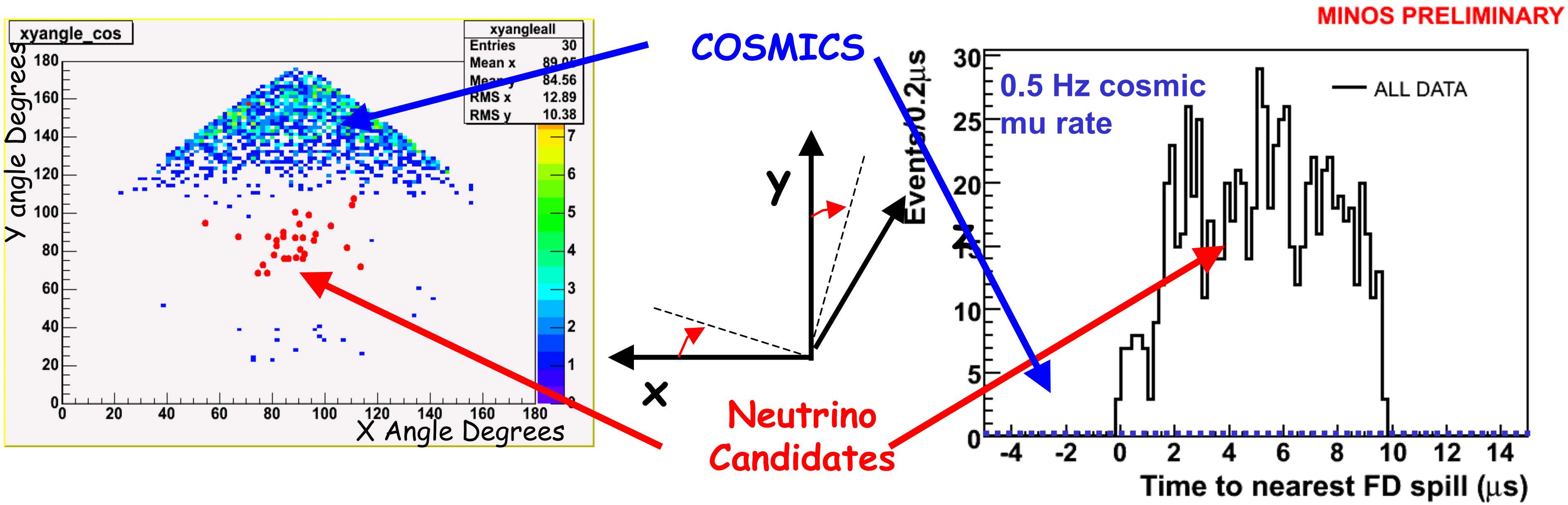
Special thanks to everyone who helped to maintain such a high livetime during this period!

Far Detector live time is 99%



Far Detector Data : Selecting Beam Induced Events

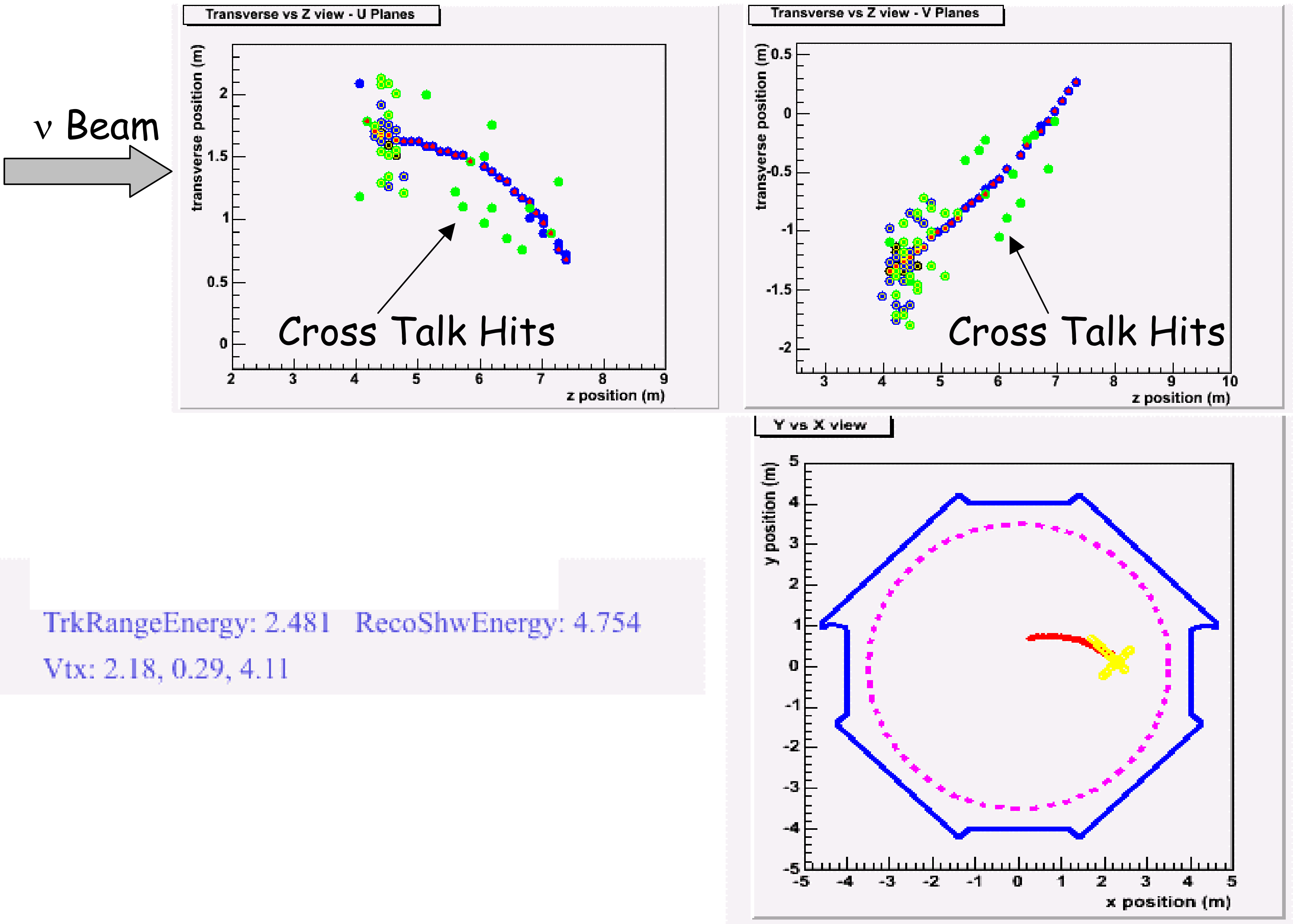
Far detector neutrino events have very distinctive topology and timing



•Time stamping of the neutrino events is provided by two GPS units (located at Near and Far detector sites).

•Analyzing 7.0 million “fake” triggers 0.8 non neutrino events are expected in the Analysis Sample.

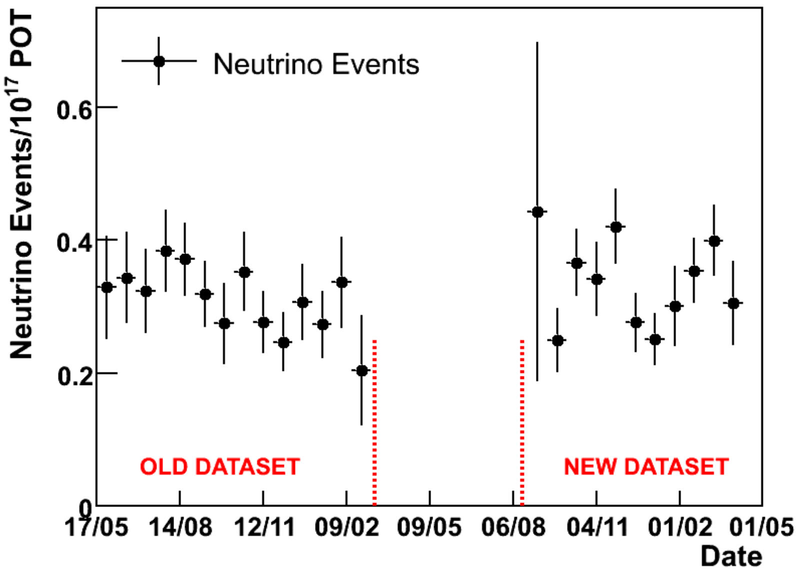
Far Detector Neutrino Events

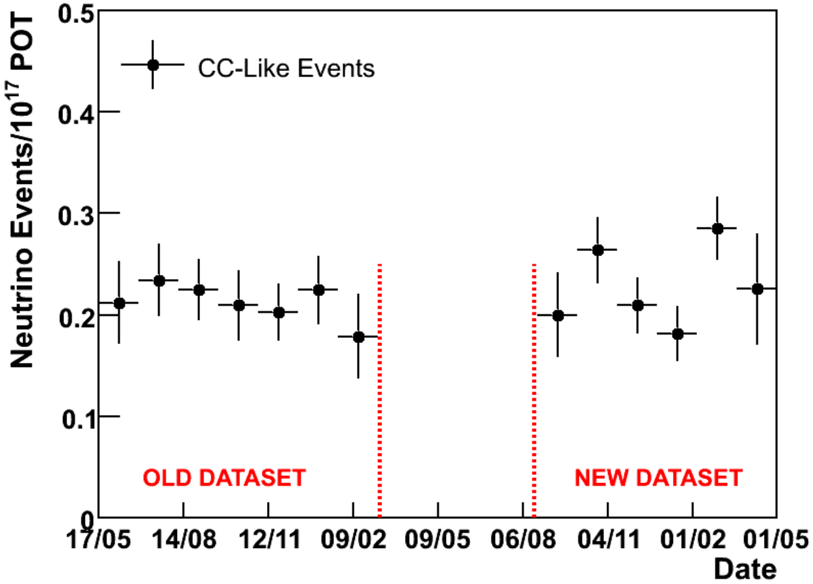


TrkRangeEnergy: 2.481 RecoShwEnergy: 4.754

Vtx: 2.18, 0.29, 4.11

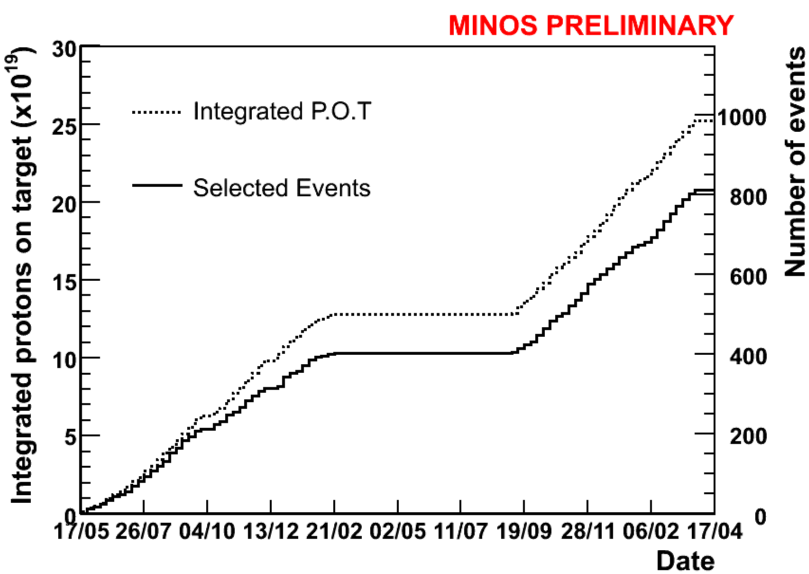
Far Detector Beam Data vs Time and POT's



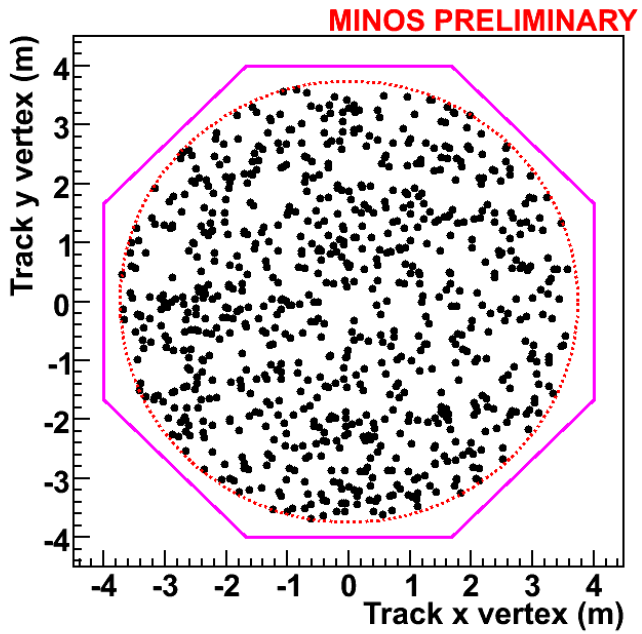


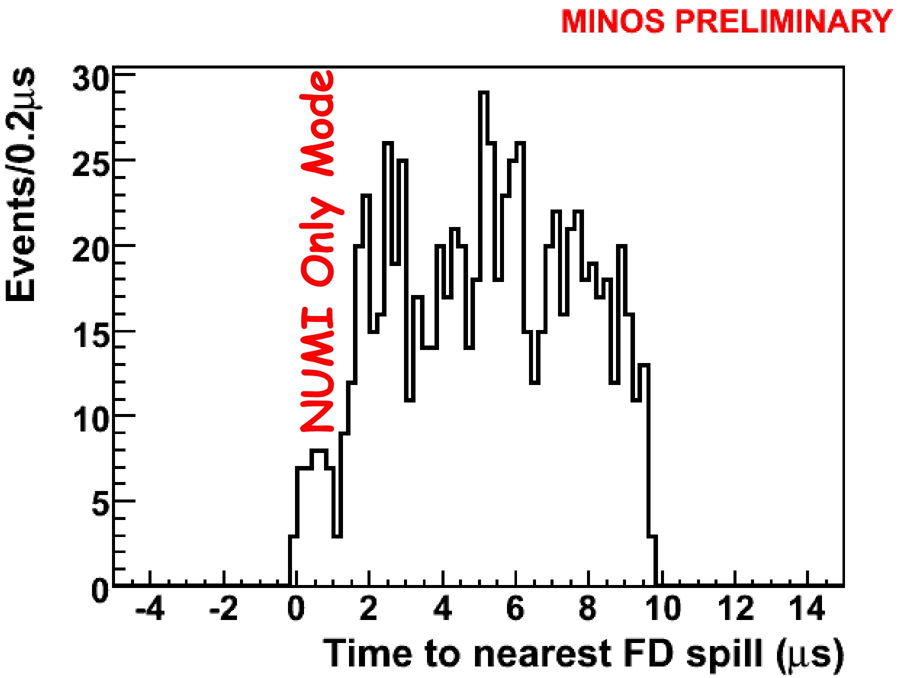
•Neutrino events per POT's are flat as a function of time.

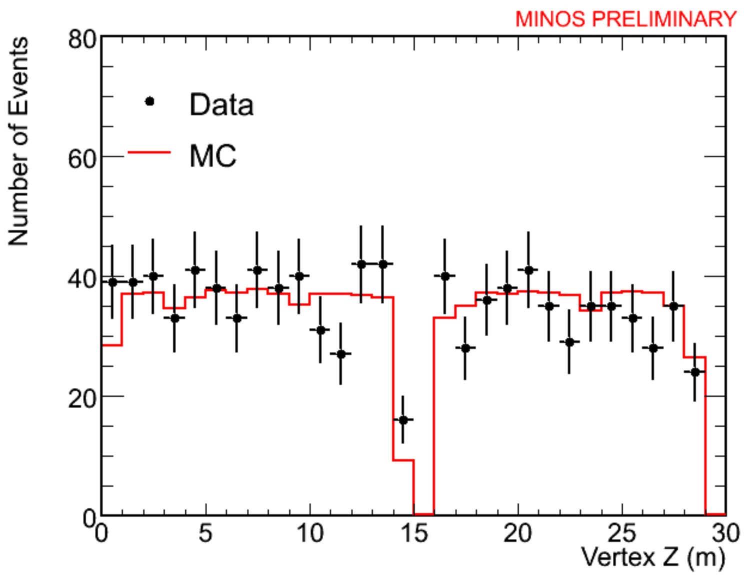
•Neutrino events follow integrated POT's nicely.



Far Detector Beam Data:Vertices and Timing







Timing and topological characteristics of beam neutrino event candidates in agreement with expectations.

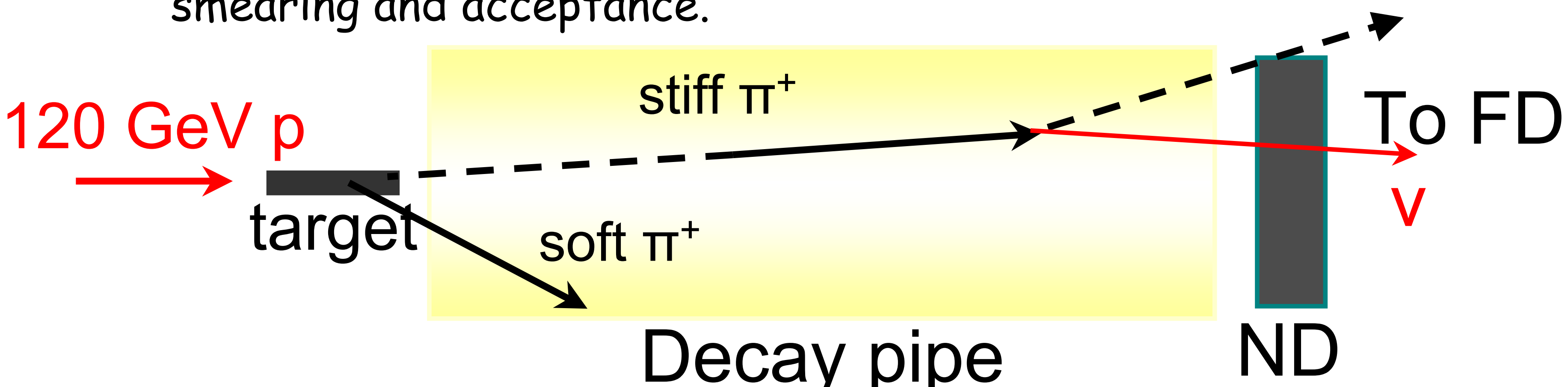
Predicting the Unoscillated FD Spectrum

- **There are two general methods for predicting the unoscillated Far Detector spectrum:**
  - **Near Detector "Data Driven":**
    - Measured ND spectrum is directly used to predict FD Unoscillated spectrum.
    - FD Prediction depends **very weakly on details of the hadron production and cross section models.**
  - **Near Detector "Fit Based":**
    - Hadron production and cross section models are "tuned" by fitting the measured ND spectrum.
    - **Tuned MC is then used as the FD unoscillated spectrum.**
    - **Disadvantage: If the models are "inadequate", the description of the Near and Far Detector Data will be inadequate as well.**
  - ***We have developed two different methods from each category. We choose as primary the "Data Driven" "Beam Matrix Method" since it gives the smallest systematic error.***

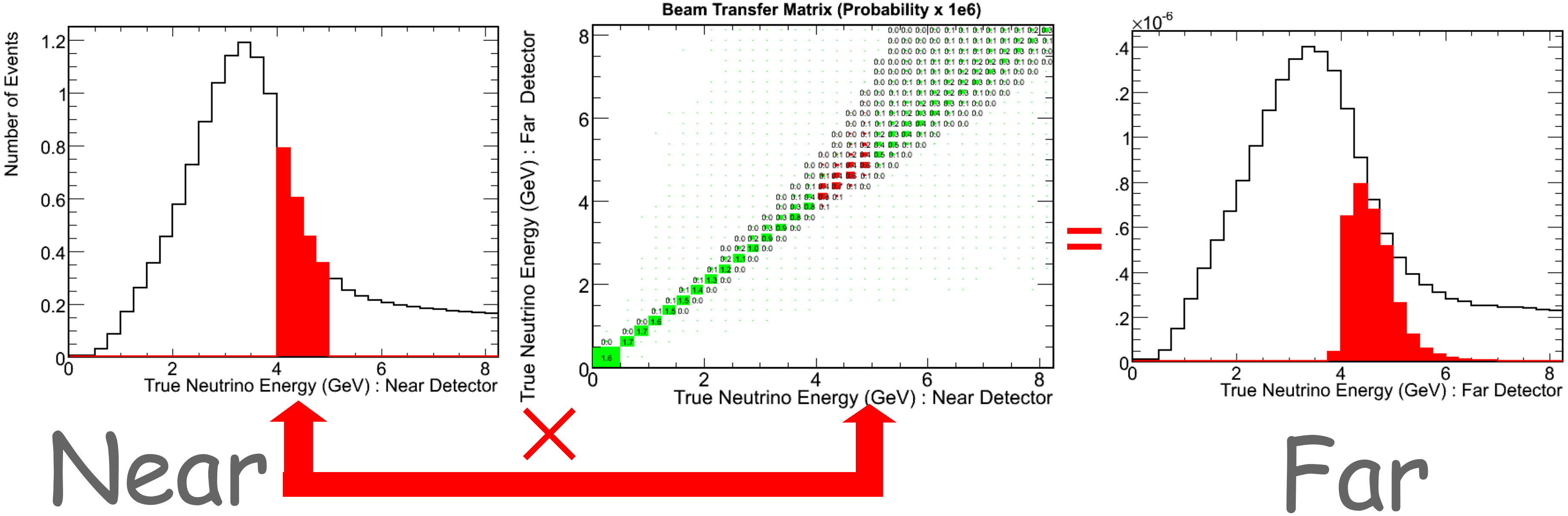
Predicting Unoscillated FD Spectrum: Beam Matrix Method

- **Use the "Beam Matrix" method** with which **beam modeling and cross sections uncertainties cancel (to a large extent)** between the two detectors.

- **The "Beam Matrix" method uses :**
  - The ND reconstructed energy distribution (Data),
  - The knowledge of pion/kaon 2-body decay kinematics and the geometry of our beamline,
  - Our Monte Carlo to provide necessary corrections due to energy smearing and acceptance.



"Beam Matrix "Method : Near to Far extrapolation

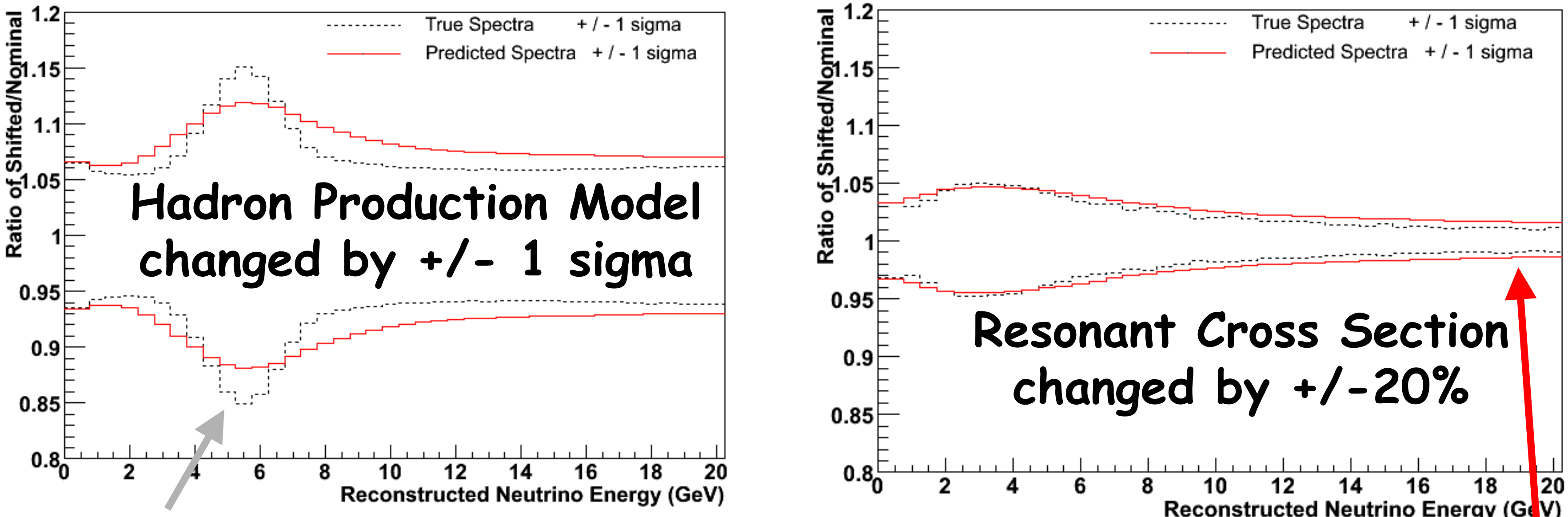


- Beam Matrix provides a very good representation of how the far detector spectrum relates to the near one.

- Beam Matrices that correspond to different hadron production models are very similar (spread in each column determined primarily by the geometry of the beamline)

Beam Matrix Method : Systematics

Beam Modeling & Cross Section Uncertainties Cancel to a large extent



Ratio of true Spectra to nominal MC : shows the magnitude of the Change due to systematic uncertainty under study

Ratio of predicted spectra to nominal MC : shows how accurately this method predicts the true spectra.

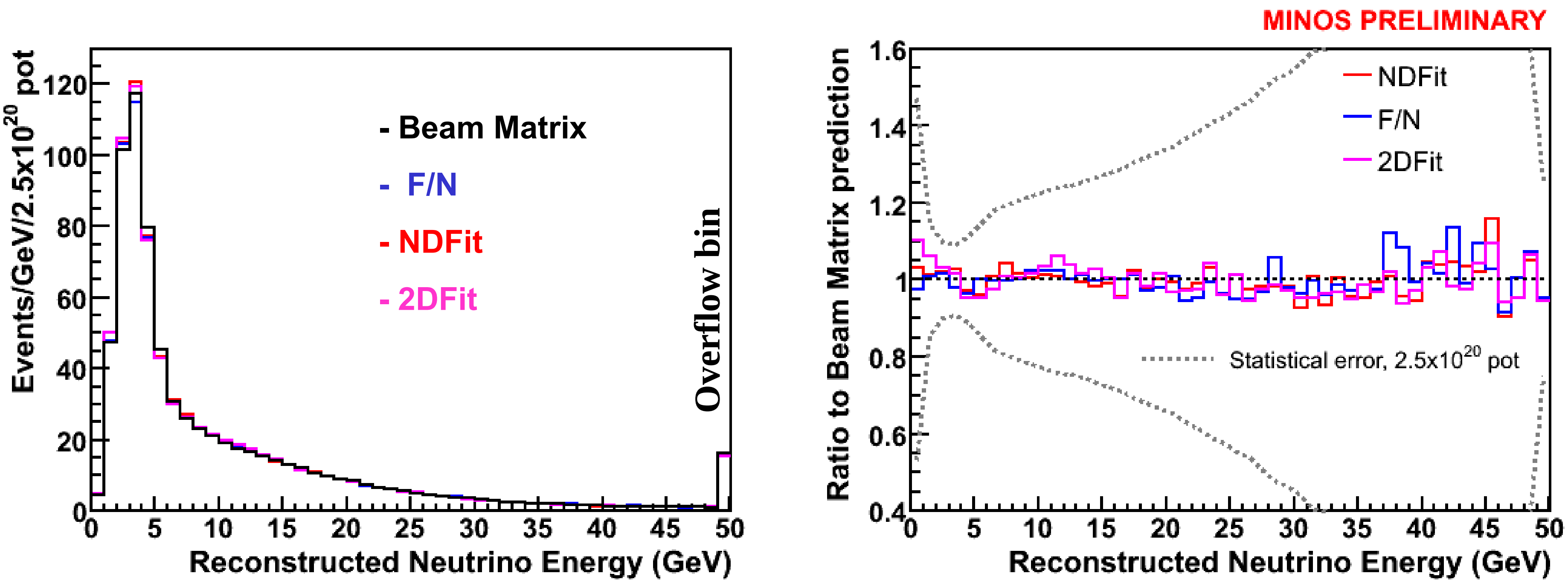
Difference between Black and Red lines is a measure of the cancellation of the systematic uncertainty (zero difference means systematic has cancelled entirely between Near and Far)

Remaining systematic uncertainties

- Beam and cross section uncertainties using the Beam Matrix Method cancel to a very large extent.
- The main remaining systematic uncertainties are Near/Far normalization, absolute hadronic energy scale and NC contamination.

Uncertainty	Shift in Δm^2 (10^{-3} eV^2)	Shift in $\sin^2(2\theta)$
Near/Far normalization ±4%	0.065	<0.005
Absolute hadronic energy scale ±10%	0.075	<0.005
NC contamination ±50%	0.010	0.008
All other systematic uncertainties	0.041	<0.005
Total systematic (summed in quadrature)	**0.11**	**0.008**
Statistical error (data)	**0.17**	**0.080**

Predicting the Un-Oscillated Spectrum : Alternative Methods



Results from all four extrapolation methods in good agreement with each other at the few (<4%) percent level.

Box opening

- Extensive checks on the open dataset in the FD completed.
- Analysis methods fully validated on MC datasets.
- Proceed to open the box and look at the full dataset

FD FULL DATA SET 2.50x10^{20} POT's

Far Detector CC-Like Event Selection

Cut	Number of Events
Track in fiducial volume	847
Data quality cuts	830
Timing cut	828
Beam quality cuts	812
Track quality cut	811
Track charge<=0	672
PID parameter>0.85	564
Reco Enu<200 GeV	**563** **Final Analysis Sample**

FD CC_{like} Events : Observed vs Expected

Data Sample	FD Data	Expected (Matrix Method; Unoscillated)	Data/Prediction (Matrix Method)
ν_μ CC_{like} All	563	738 ± 30	0.76 (4.4 σ)
ν_μ CC_{like} (<10 GeV)	310	496 ± 20	0.62 (6.2 σ)
ν_μ CC_{like} (<5 GeV)	198	350 ± 14	0.57 (6.5 σ)

For energies between 0-10 GeV a deficit of 38% is observed, with respect to the no disappearance hypothesis.

Oscillation Fit

- Fit to the visible energy spectrum of the selected Far detector CC events to extract the mixing parameters Δm^2 and $\sin^2 2\theta$:

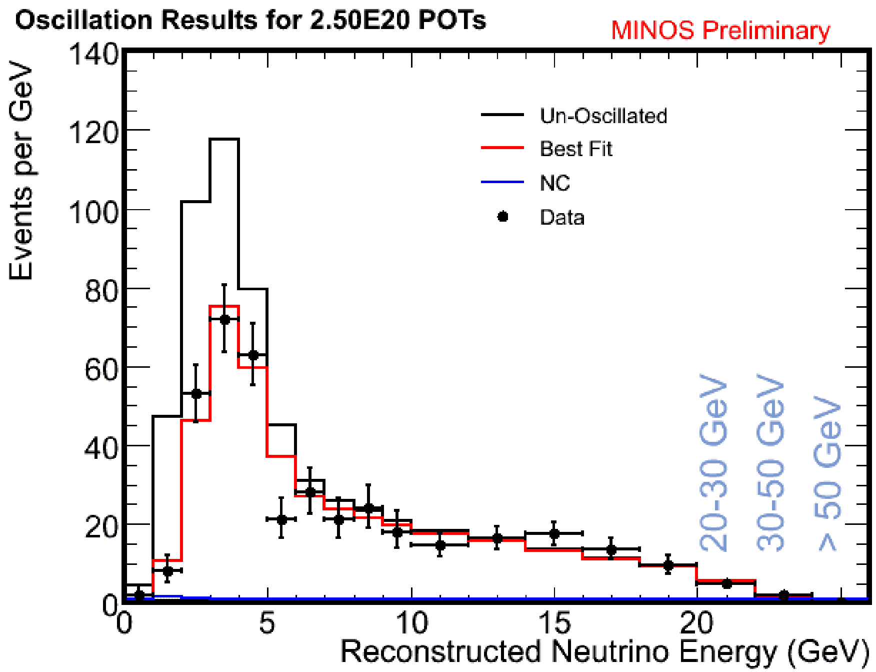
$$\chi^2(\Delta m^2, \sin^2 2\theta, \alpha_j, \ldots) = \underbrace{\sum_{i=1}^{nbins} 2(e_i - o_i) + 2o_i \ln(o_i/e_i)}_{\text{Statistical error}} + \underbrace{\sum_{j=1}^{nsyst} \frac{\Delta\alpha_j^2}{\sigma_{\alpha_j^2}}}_{\text{Systematic errors}}$$

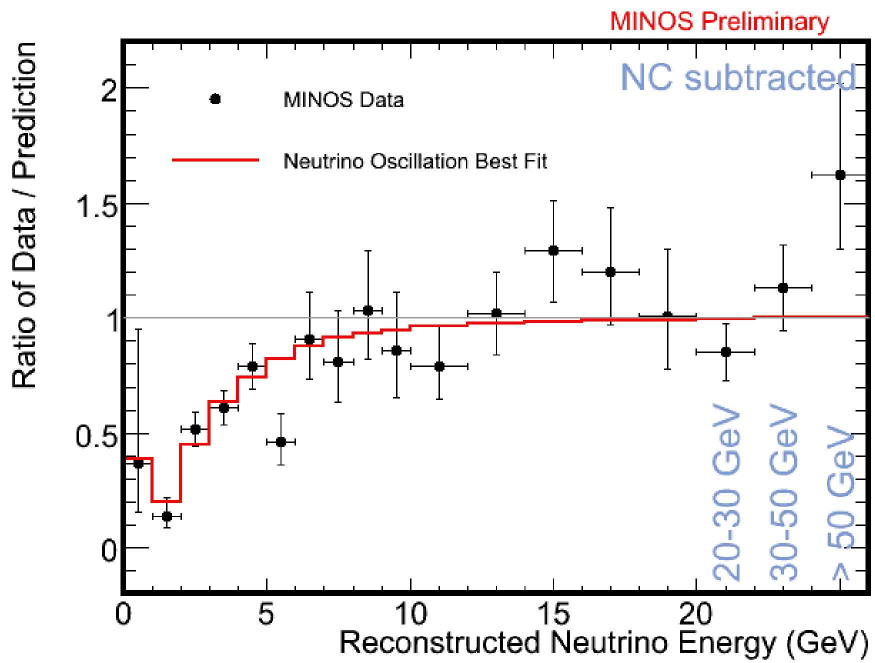
- Systematic uncertainties:

  4% N/F normalisation
  10% Absolute shower energy scale
  50% NC background Contamination

  common to near and far detectors

FD CC_{like} Events: Best Fit Spectrum





Oscillation Hypothesis best fit

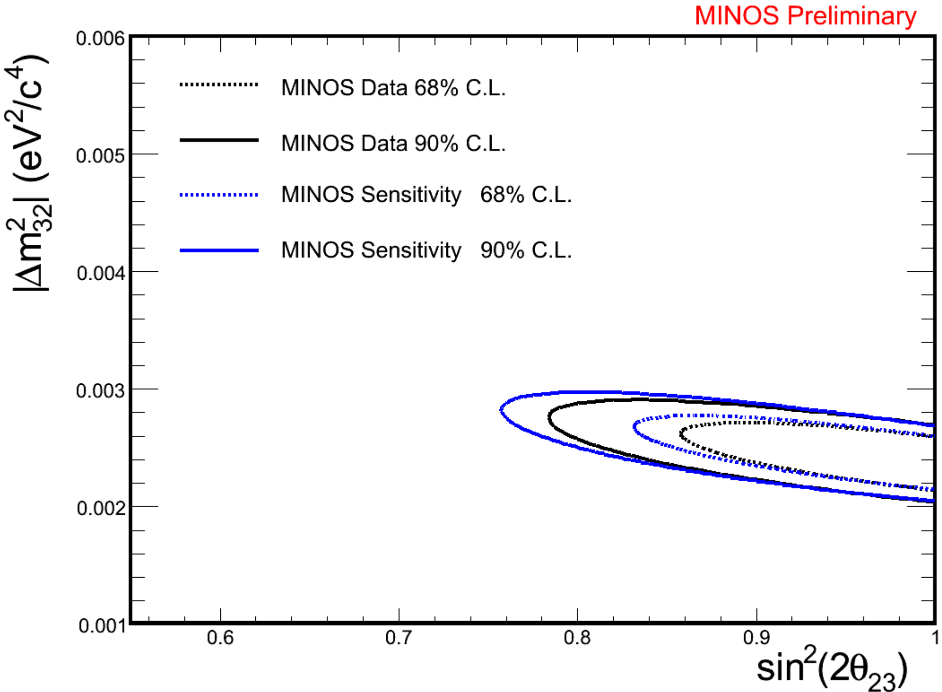
χ^2 /n.d.f = 41.2/34 = 1.2 P(χ^2,n.d.f) = 0.18

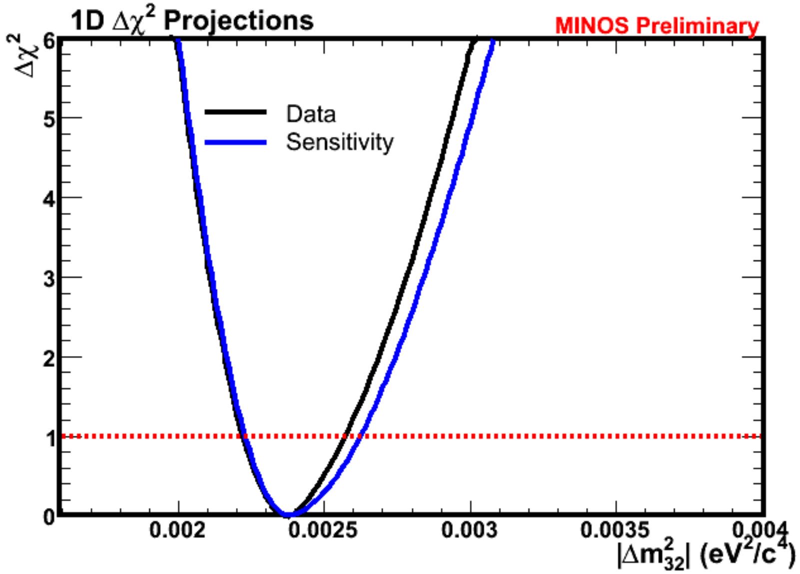
No Disappearance Hypothesis

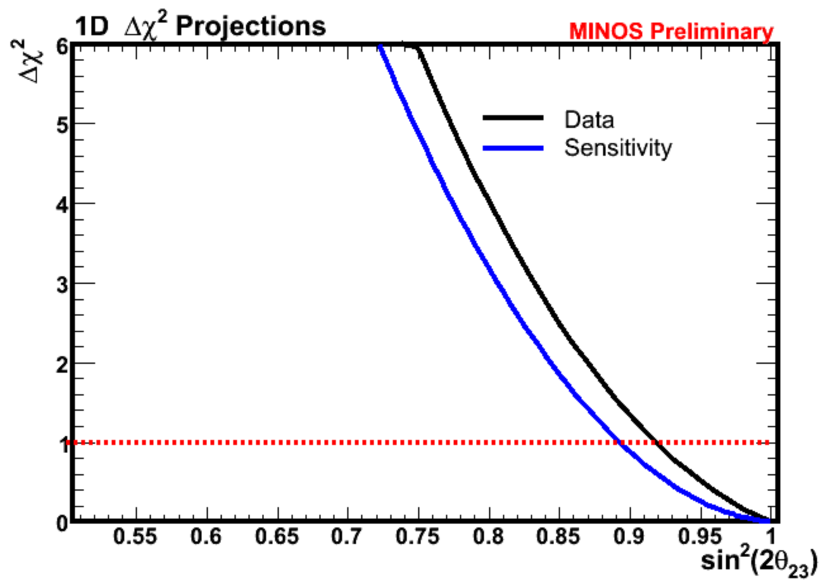
χ^2 /n.d.f = 139.2/36 =3.9 P(χ^2,n.d.f) is negligible

- Strong energy-dependent suppression of ν_μ events observed.
- Consistent with the neutrino oscillation hypothesis.

FD CC_{like} Events: MINOS Allowed Region







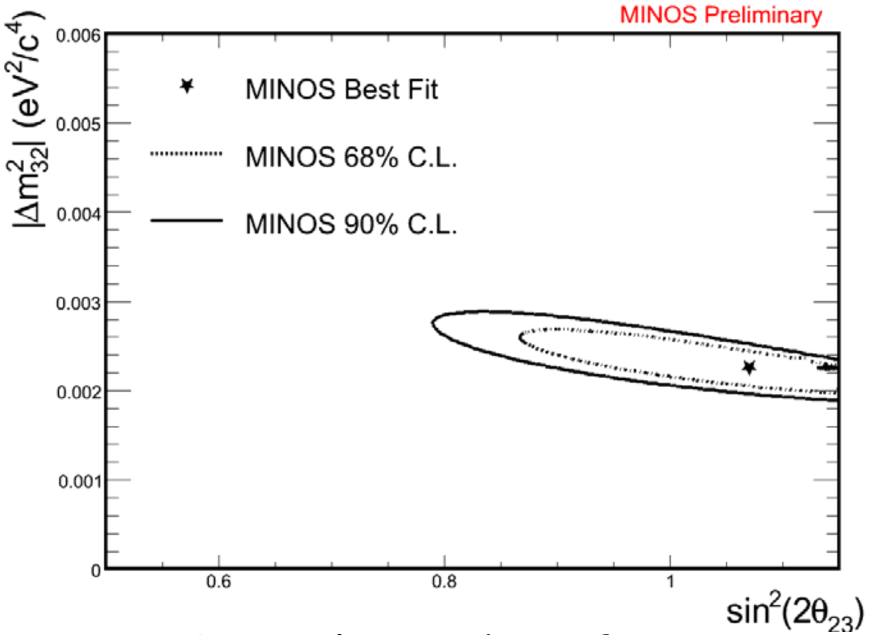
Best Fit Values when fit Constrained to the Physical Region

$$|\Delta m_{32}^2| = 0.00238^{+0.00020}_{-0.00016}\ \text{eV}^2/\text{c}^4$$

$$\sin^2(2\theta_{23}) = 1.00_{-0.08}$$

$$\chi^2/\text{n.d.f} = 41.2/34 = 1.2$$

Best Fit: No constraint to physical Region



<u>Best Fit Values when fit Not Constrained to the Physical Region</u>

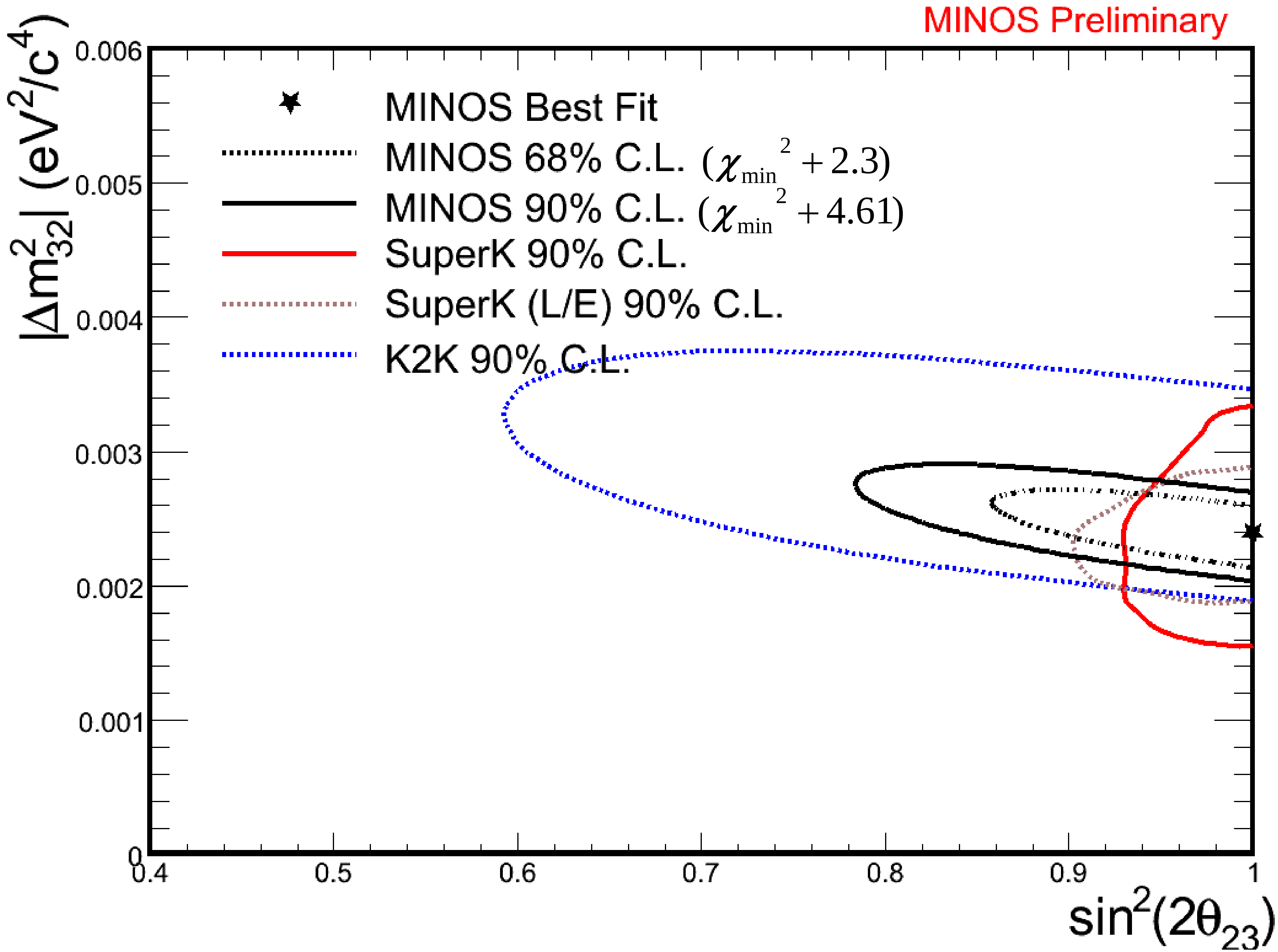
$$|\Delta m_{32}^{2}| = 0.00226 \quad eV^2/c^4$$

$$\sin^{2}(2\theta_{23}) = 1.07$$

$$\chi^2/\text{n.d.f} = 40.9/34 = 1.2$$

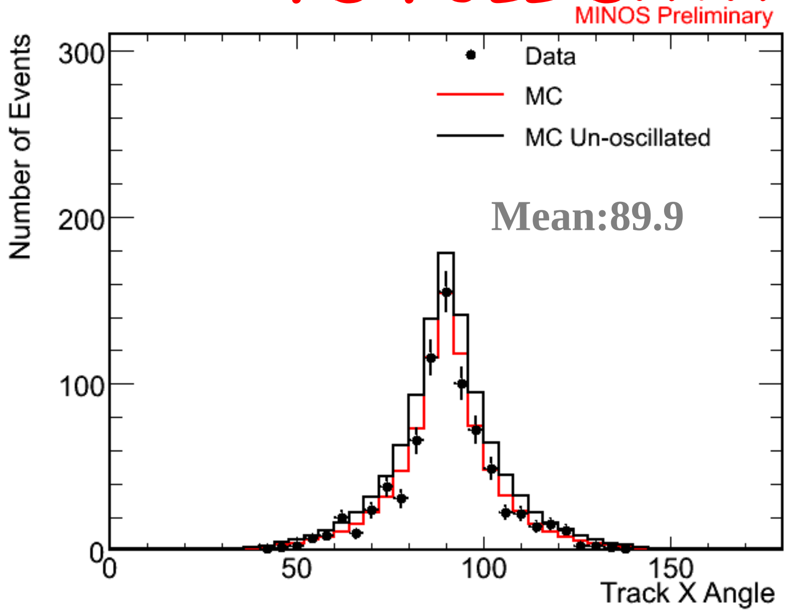
- **The Feldman-Cousins Method is one that insures coverage.**
- We have **already evaluated the effect when only statistical uncertainties are considered**, we plan to fully exploit the FC Method for our final results.
- Given the initial statistical studies, **the Feldman - Cousins approach indicates that our current Confidence Intervals are slightly conservative (over-coverage)**

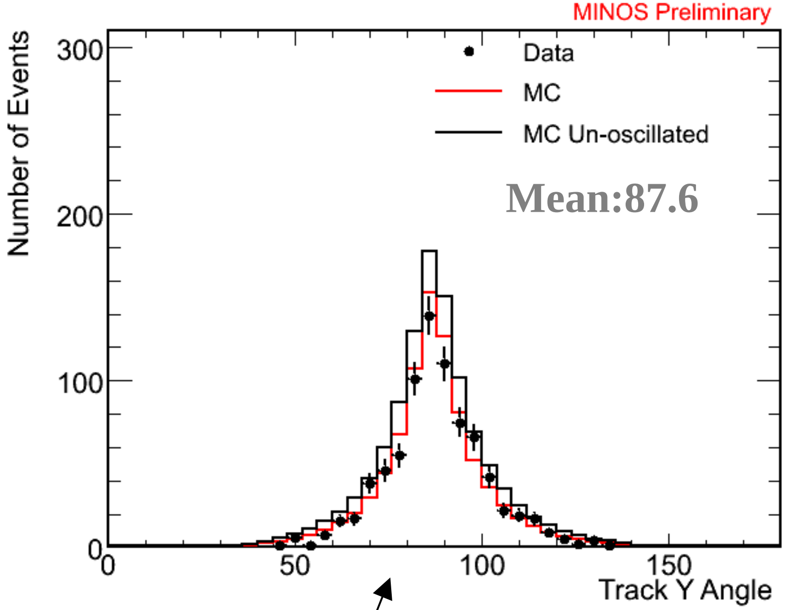
FD CC_{like} Events: MINOS Allowed Region



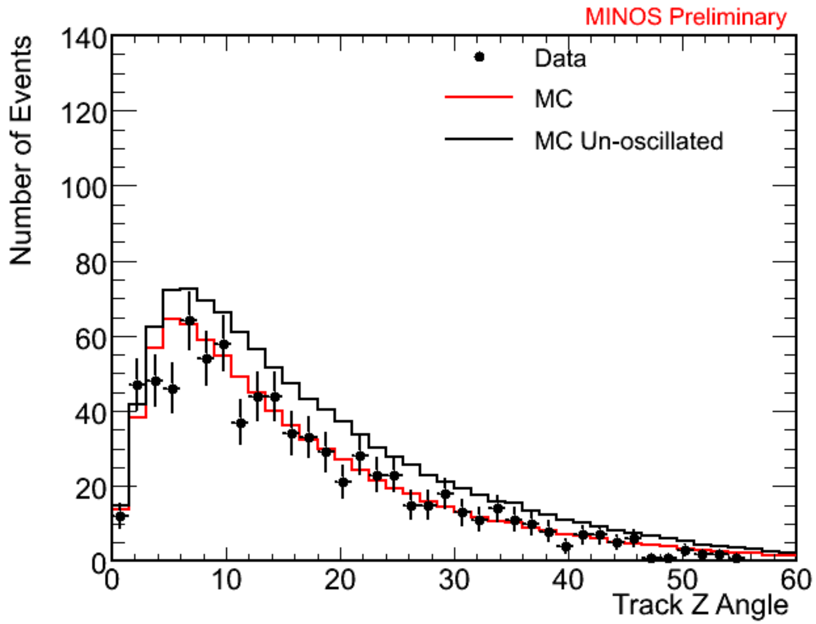
FD Distributions : Track Angles

FD FULL DATA SET 2.50×10^{20} POT's





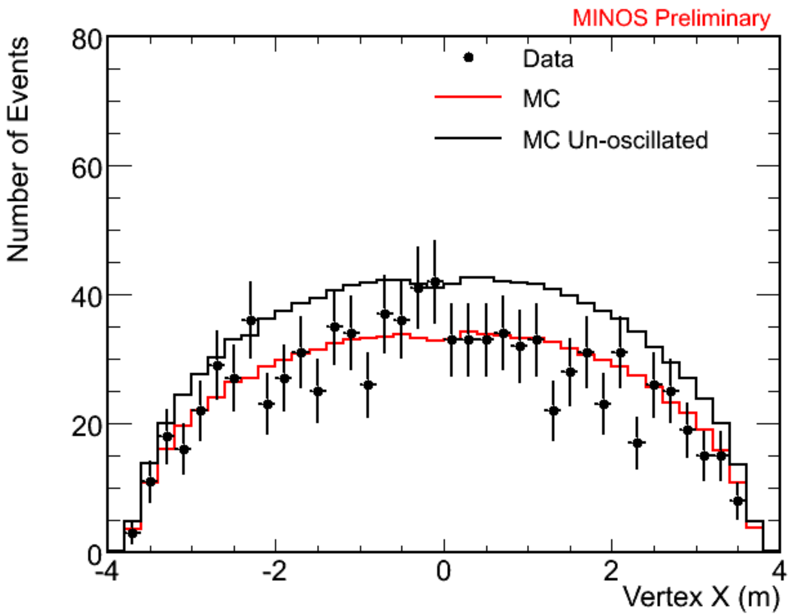
Neutrinos point ~3^0 up in the FD!!

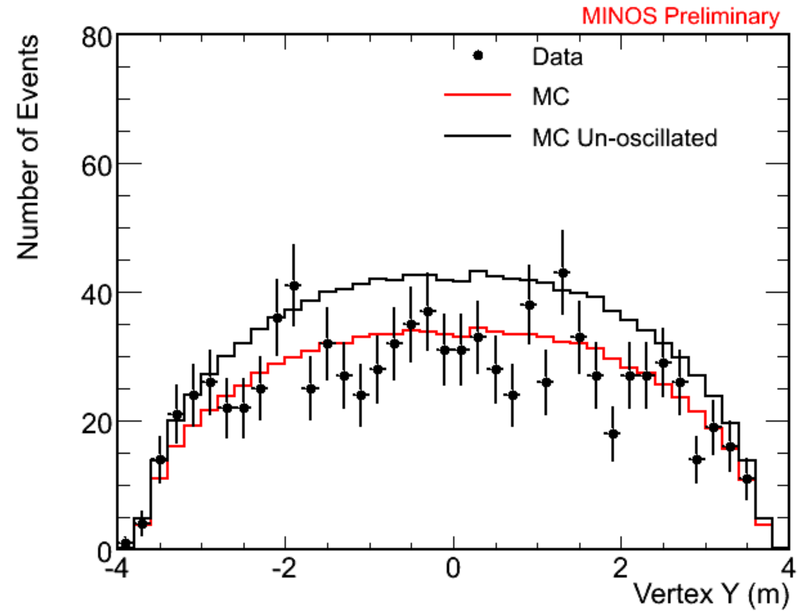


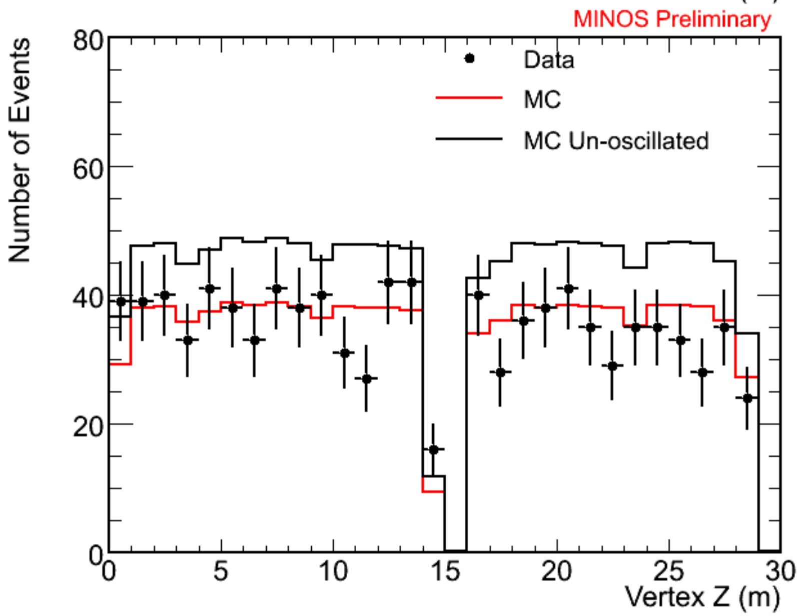
Agreement between Data and oscillation best fit very good.

FD Distributions : Vertices

FD FULL DATA SET 2.50x10^{20} POT's



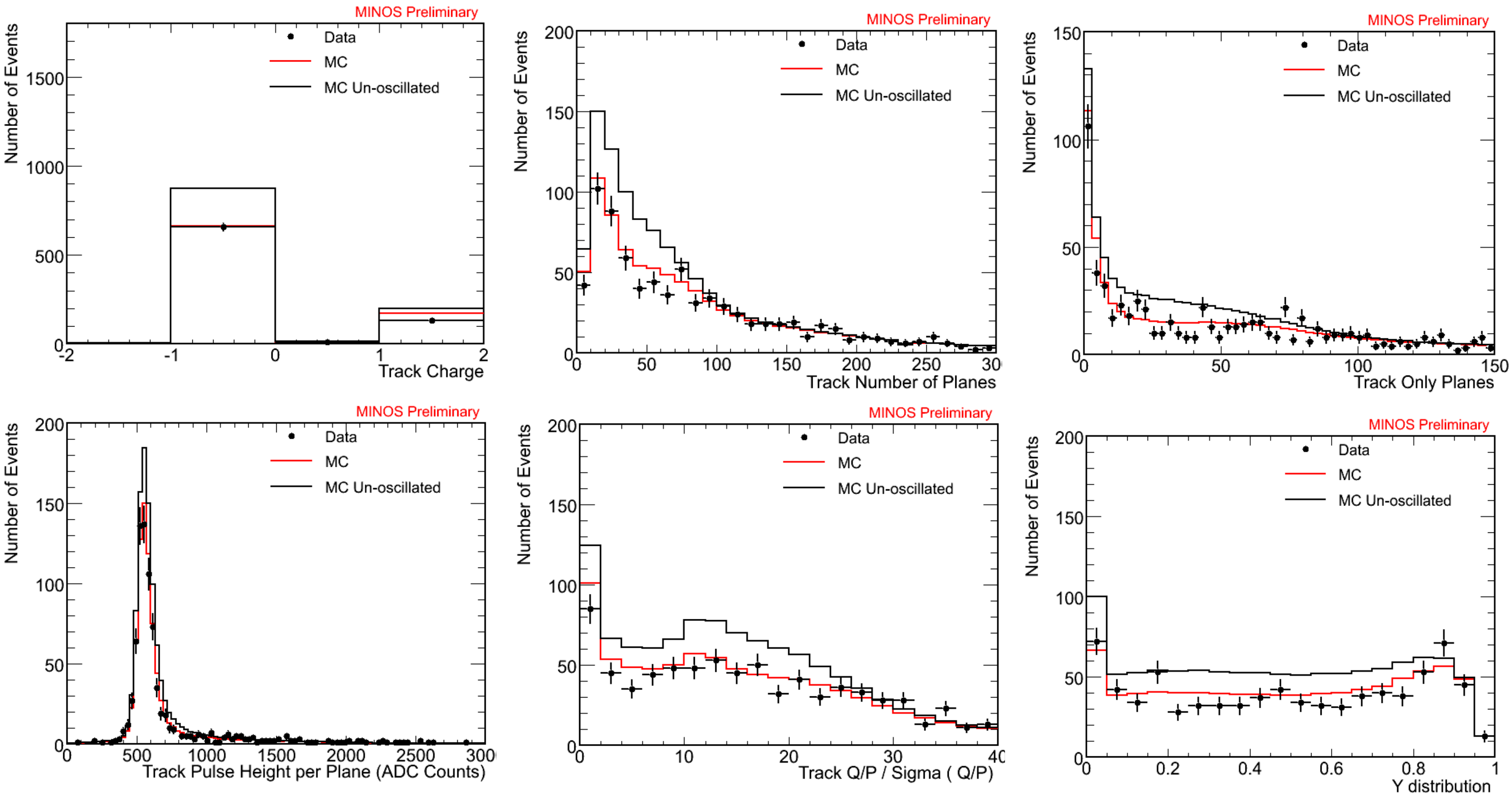




Agreement between Data and oscillation best fit very good.

PID Input Variables

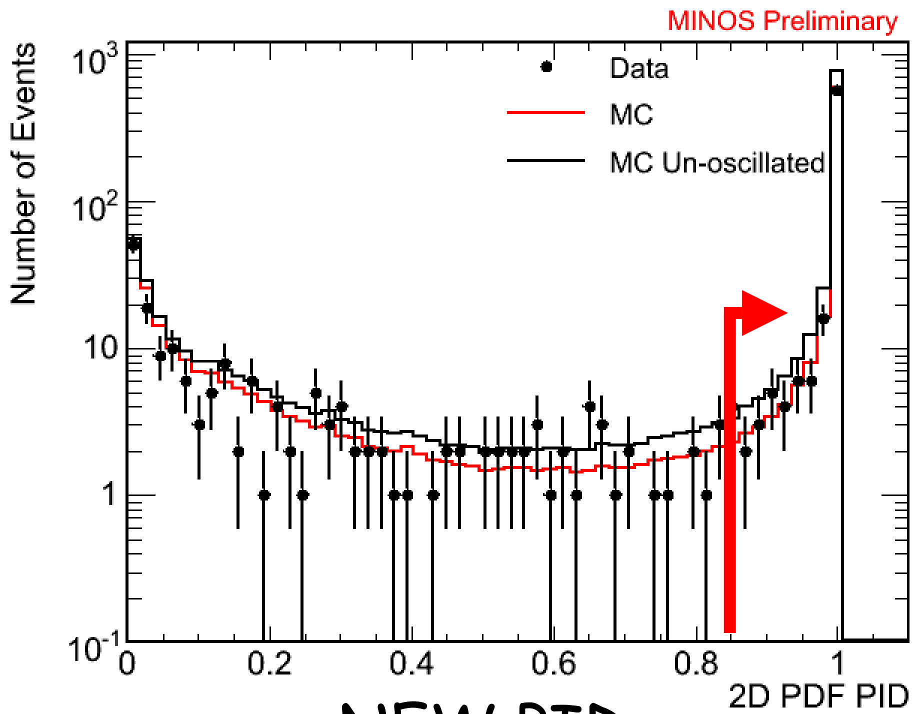
FD FULL DATA SET 2.50×10^{20} POT's



Agreement between Data and oscillation best fit very good

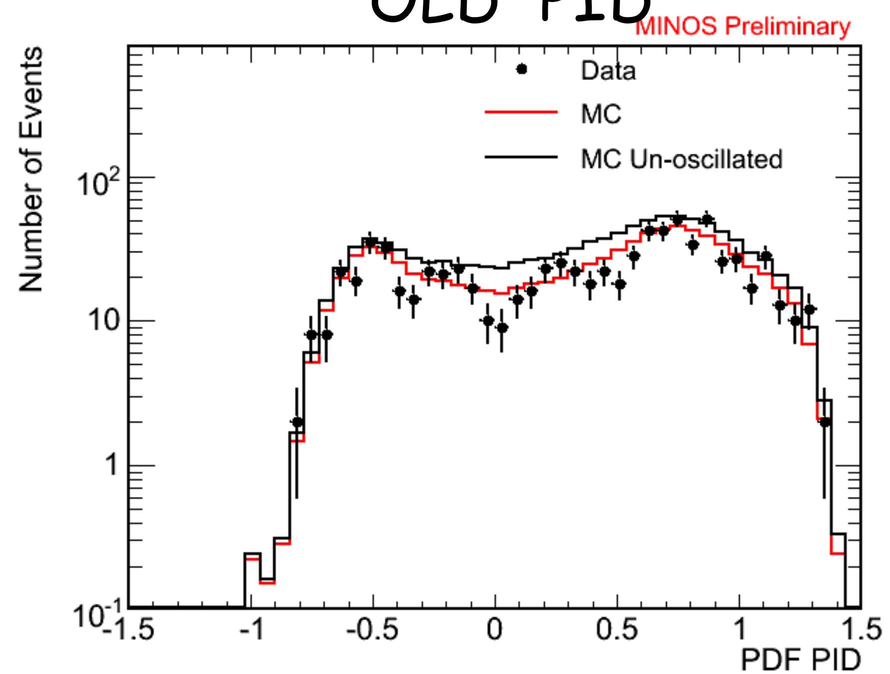
PID Distributions

FD FULL DATA SET 2.50x10^{20} POT's



NEW PID

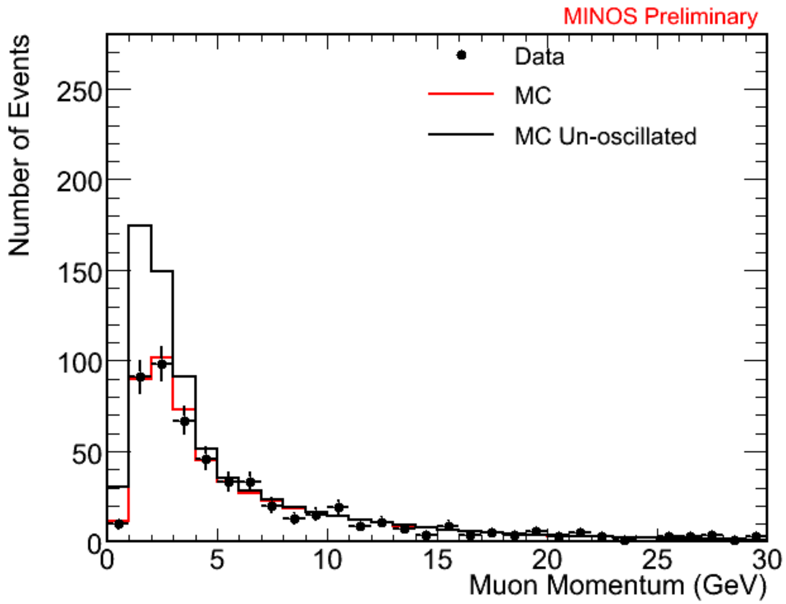
OLD PID

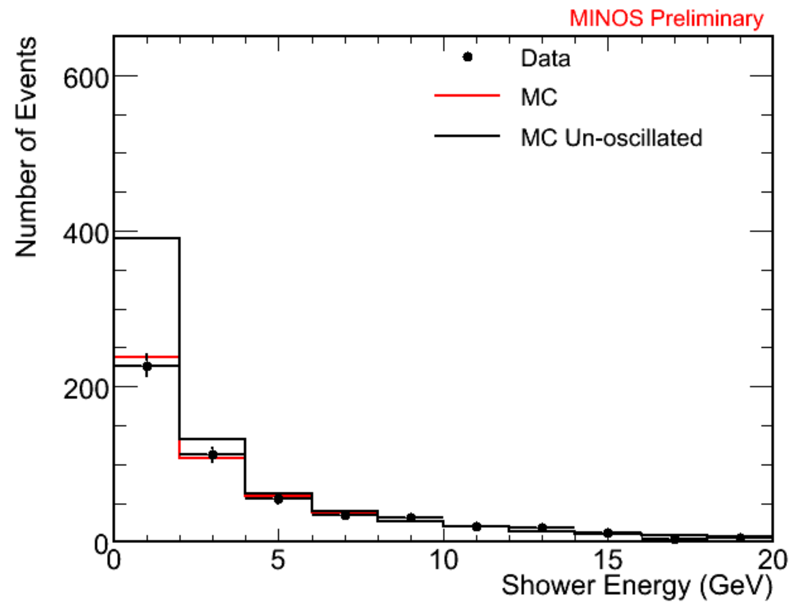


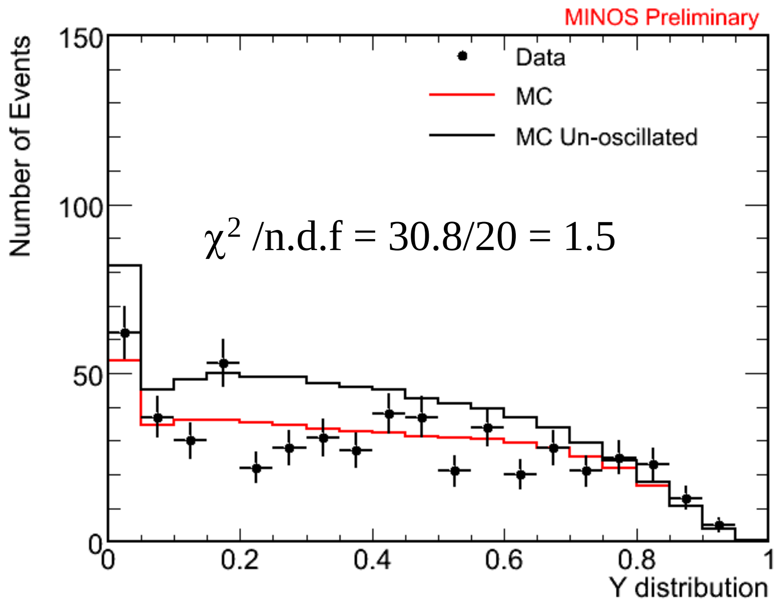
Agreement between Data and oscillation best fit very good

FD CC_{like} Events:Kinematic Distributions

FD FULL DATA SET 2.50×10^{20} POT's

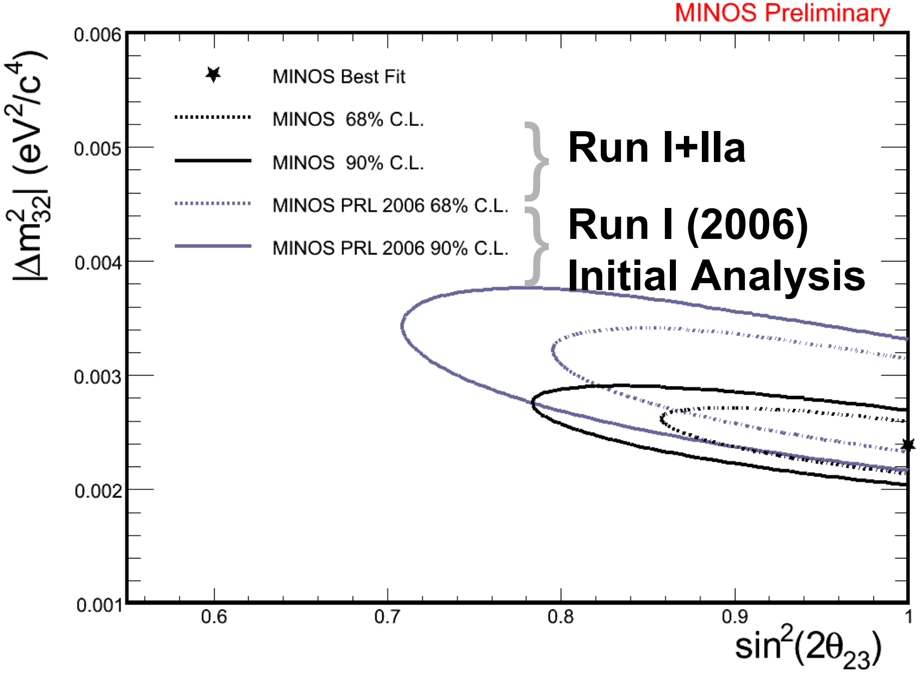


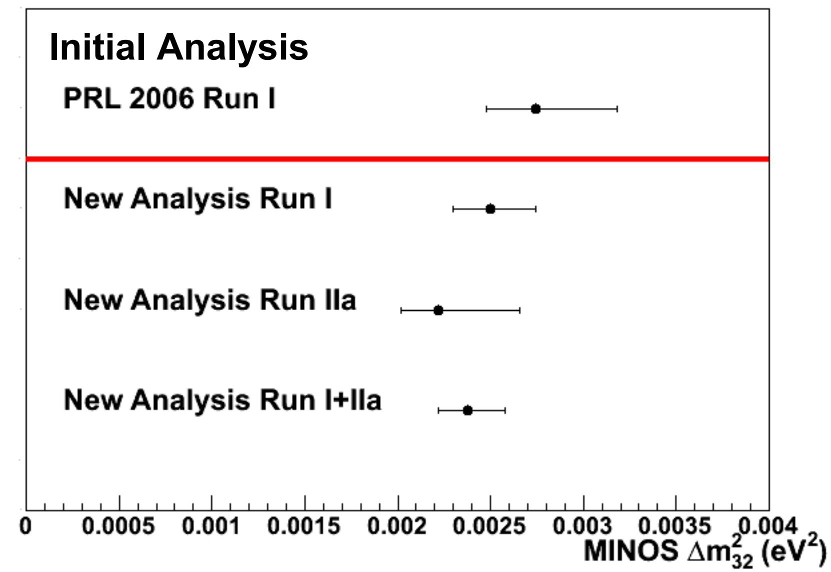


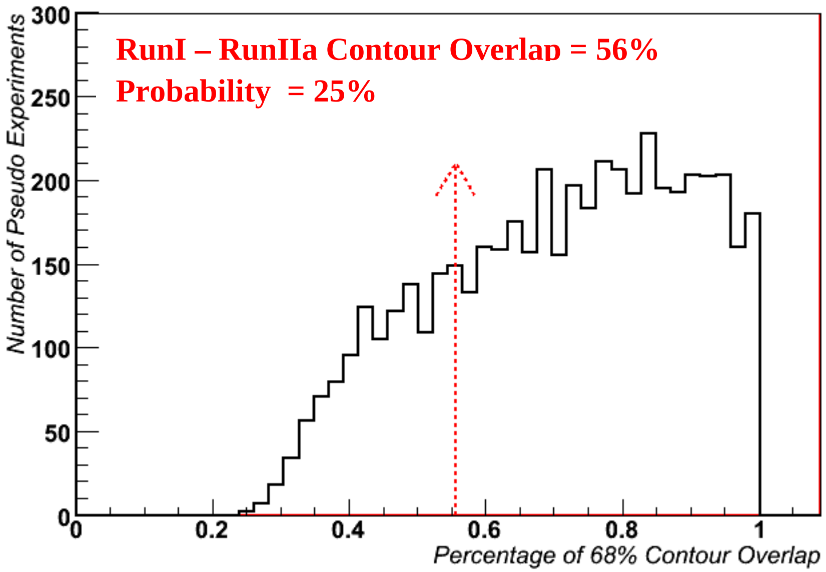


Agreement between Data and oscillation best fit very good

PRL 2006 – Current Results







Best Fit value changed due to :

1) Partially statistics (new events)

2)The systematic shift in Shower energy by 1 σ with the new Intranuclear Re-scattering Model.

Summary / Outlook

- **The MINOS new result increases further (w.r.t our previous one) the precision on the knowledge of the "atmospheric mass squared difference", which is important for the next generation neutrino oscillation experiments.**

- The MINOS result is in agreement with previous measurements (SuperK and K2K). The fit of the **Neutrino Energy Spectrum under the oscillation hypothesis yields a Probability of 18%.** The fit to the Neutrino Energy Spectrum under the hypothesis of **no disappearance yields a negligible probability**.

- The systematic uncertainties of this measurement are well under control.

- **With the MINOS increased statistics, we will be able to test "exotic" models and possibly disfavor them with large significance!**

- **Analyses of Neutral Current, Electron Neutrino Appearance, and Neutrino Cross Sections are underway…**

- **Stay tuned!!**

Acknowledgements

- On behalf of the MINOS Collaboration, we would like to express our gratitude to the *many Fermilab groups who provided technical expertise and support in the design, construction, installation and operation of the experiment.*

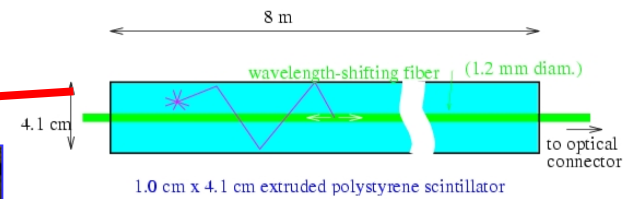
- We would also like to gratefully acknowledge financial support from the following institutions: DOE, NSF, University of Minnesota (and the Minnesota DNR for hosting us) and STFC (UK)

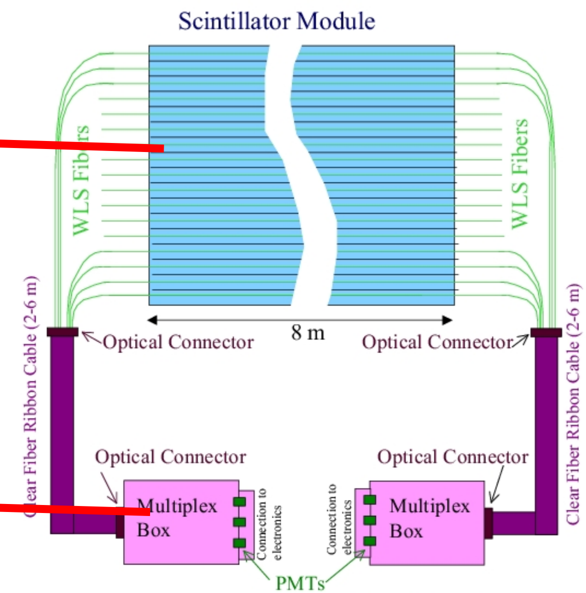
BACKUP SLIDES

Detector Technology

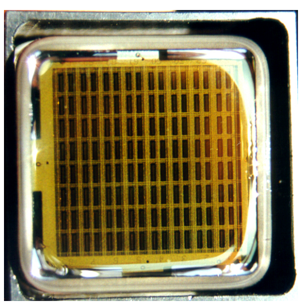
MINOS Near and Far detectors are functionally identical: share same detector technology and granularity:

Scintillator strip

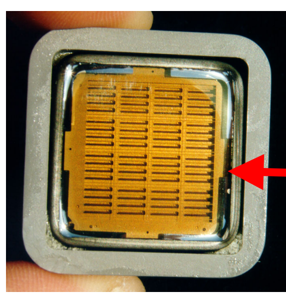




Objects not to scale



M64 PMT



M16 PMT

Analysis Changes w.r.t. published (Phys.Rev.Lett.97(2006)19180) Analysis

Reconstruction – Event Selection

Improved track reconstruction :

1) **More events satisfy pre-selection track quality related criteria**
(+4% expected, +6% observed (26 events))

Improved Event Selection with the use of 2D PDFs (correlations are taken into account) and more Discriminating variables :

2) **Increased efficiency for selecting ν_μ CC**
(+1.0% expected,+2.1% observed (11 events))

3) **Increased background rejection (less NC contamination)**

Enlarged Far Detector Fiducial Volume and relaxed 30 GeV Energy Cut on Analysis sample:

4) **Increased overall neutrino selection efficiency**
(+3.2% expected, +3.4% observed due to fiducial volume (17 events)
+ 9.6% expected, + 12.6% observed due to 30 GeV energy cut(63 events))

Schematic Description of the "Beam Matrix" Method

A)
$$E^{\text{Reconstructed}}_{\textit{Near}\ \text{CC-like}} \Rightarrow E^{\textit{True}}_{\textit{Near}\ \text{CC}}$$

Correction for purity =>Reconstructed=>True =>Correction for efficiency

B)
$$E^{\textit{True}}_{\textit{Near}\ \text{CC}} \Rightarrow E^{\textit{True}}_{\textit{Far}\ \text{CC}}$$

BEAM MATRIX

C)
$$E^{\textit{True}}_{\textit{Far}\ \text{CC}} \Rightarrow E^{\text{Reconstructed}}_{\textit{Far}\ \text{CC-like}}$$

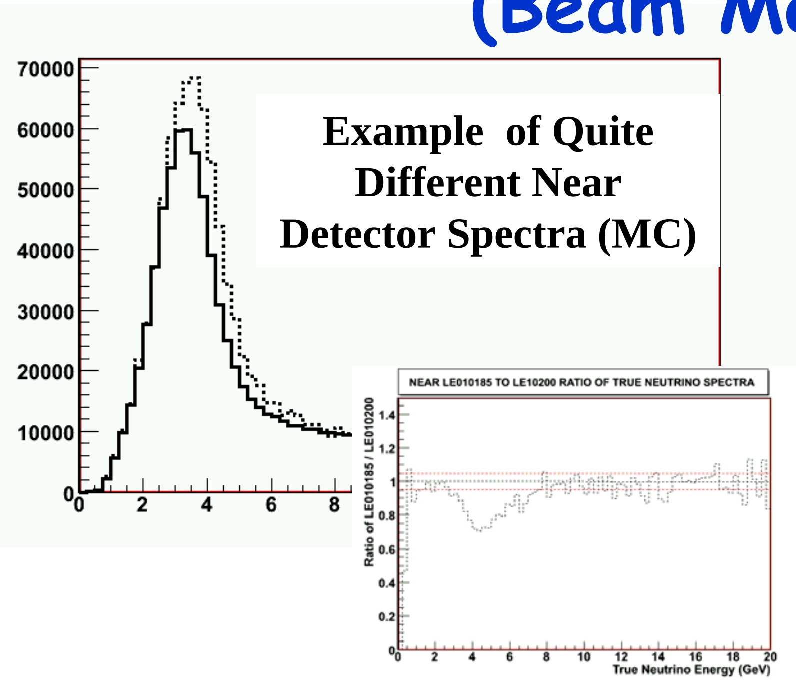
Obtain CC Oscillated Spectrum :

i) Oscillate => True => Reconstructed => Correction for efficiency

Obtain NC Background :

ii) Unoscillated True => Reconstructed =>Use Purity

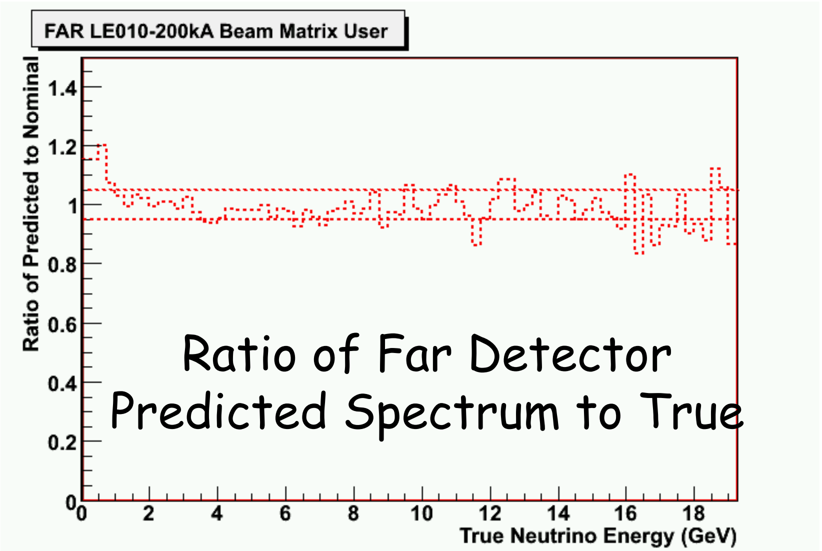
Why Beam Modeling uncertainties Cancel (Beam Matrix Method)



Example of Quite Different Near Detector Spectra (MC)

Beam Matrices that correspond to quite different near detector spectra are very similar (spread in each column determined primarily by the geometry of the beamline)

NOTE :Red dotted bands are ± 5%.



Ratio of Far Detector Predicted Spectrum to True

Method: Use instead of LE010 185 kA Beam transfer Matrix the LE010 200kA Beam transfer Matrix

These different matrices correspond to quite different "beams" as evident from the Near Detector Spectra.

However, Far Detector Prediction is quite accurate to within < 5%

Why Cross Section Uncertainties Cancel (Beam Matrix Method)

ND Spectrum **Beam Matrix** **FD Spectrum**

$$\underbrace{\begin{pmatrix} E_1 \\ E_2 \\ E_3 \end{pmatrix} \times \begin{pmatrix} \sigma_a & 0 & 0 \\ 0 & \sigma_b & 0 \\ 0 & 0 & \sigma_c \end{pmatrix}^{-1}}_{\text{ND Flux}} \times \begin{pmatrix} b_1 & 0 & 0 \\ 0 & b_2 & 0 \\ 0 & 0 & b_3 \end{pmatrix} \times \begin{pmatrix} \sigma_a & 0 & 0 \\ 0 & \sigma_b & 0 \\ 0 & 0 & \sigma_c \end{pmatrix} = \begin{pmatrix} e_1 \\ e_2 \\ e_3 \end{pmatrix} \Rightarrow$$

ND Flux ⟶ **FD Flux**

Cross Section matrices & Beam Matrix almost diagonal=>They Commute!

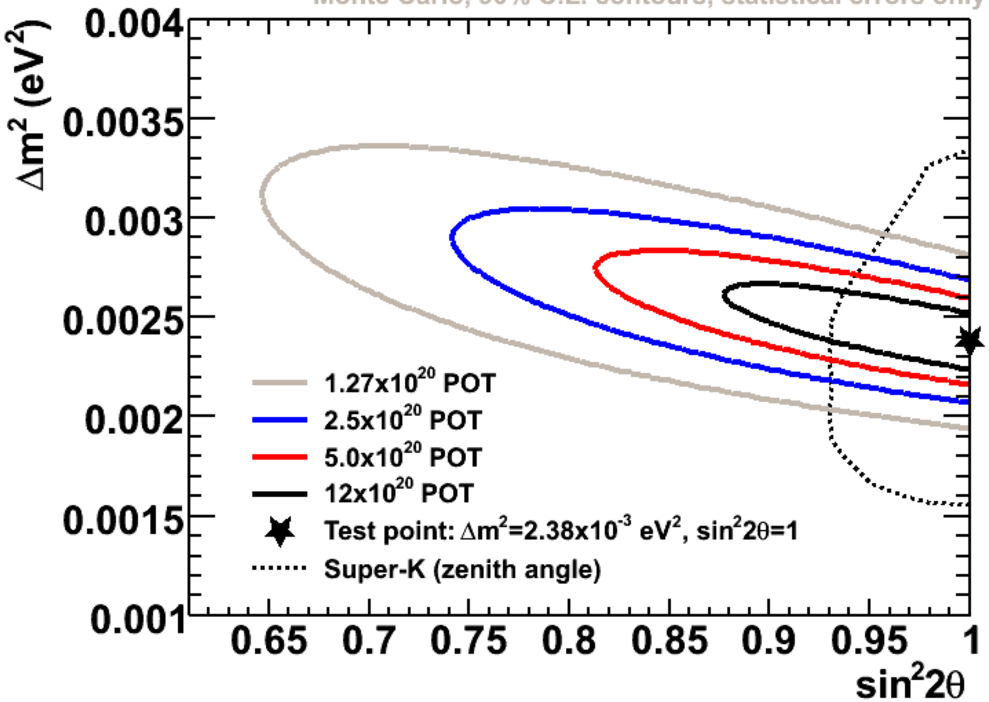
$$\Rightarrow \begin{pmatrix} E_1 \\ E_2 \\ E_3 \end{pmatrix} \times \underbrace{\begin{pmatrix} \sigma_a & 0 & 0 \\ 0 & \sigma_b & 0 \\ 0 & 0 & \sigma_c \end{pmatrix}^{-1} \begin{pmatrix} \sigma_a & 0 & 0 \\ 0 & \sigma_b & 0 \\ 0 & 0 & \sigma_c \end{pmatrix}} \begin{pmatrix} b_1 & 0 & 0 \\ 0 & b_2 & 0 \\ 0 & 0 & b_3 \end{pmatrix} = \begin{pmatrix} e_1 \\ e_2 \\ e_3 \end{pmatrix}$$

Their Product is I regardless of their values!

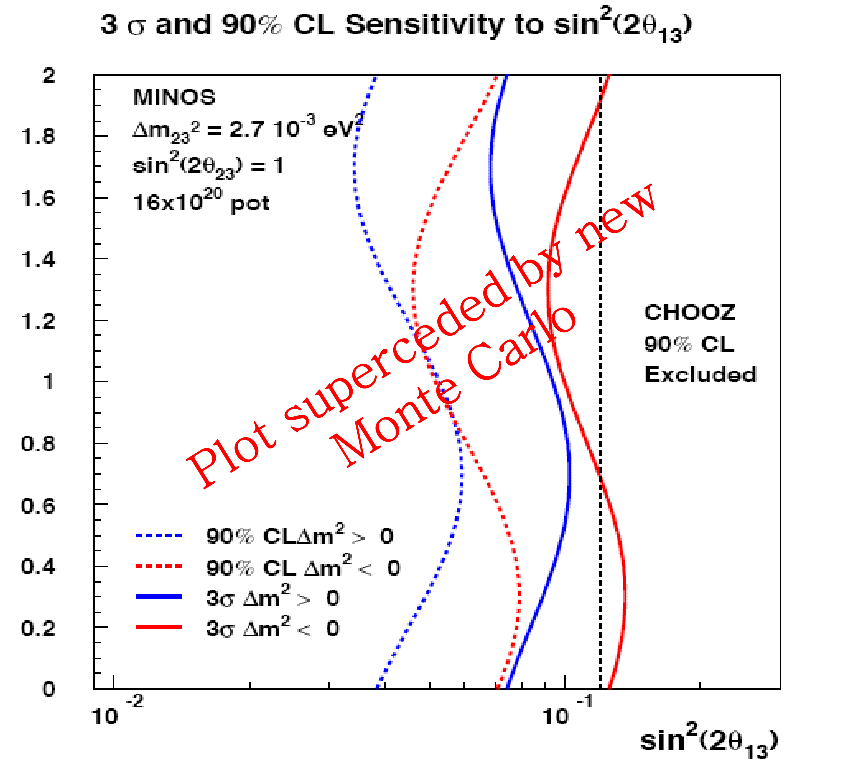
(In the limit where the Beam Matrix is diagonal)

Projected Sensitivity of MINOS

ν_μ disappearance



$\nu_\mu \rightarrow \nu_e$

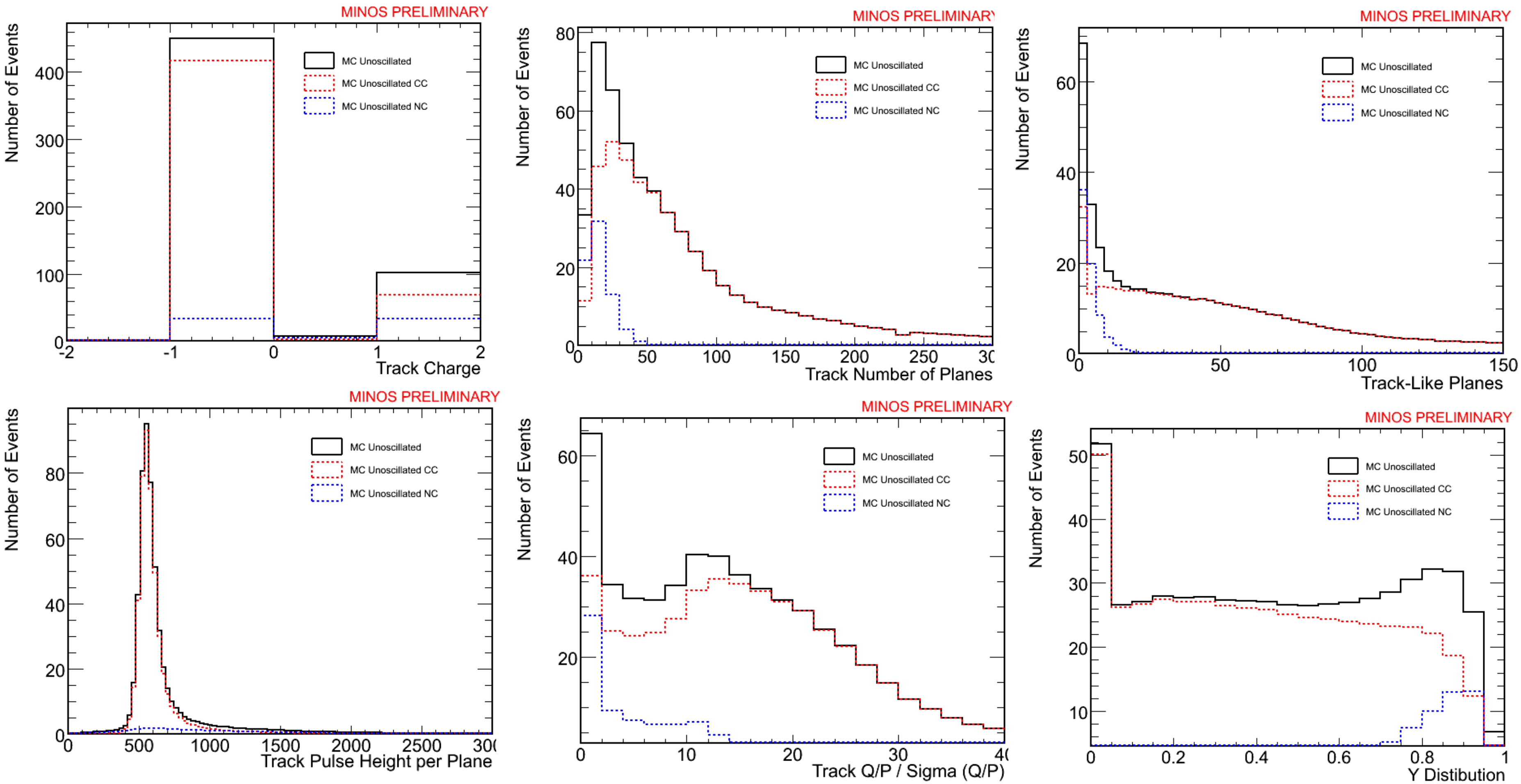


With increased statistics :

-Improve precision on $|\Delta m^2_{23}|$ and $\sin^2(2\theta_{23})$ **and test/rule out alternate models such as neutrino decay and decoherence.**

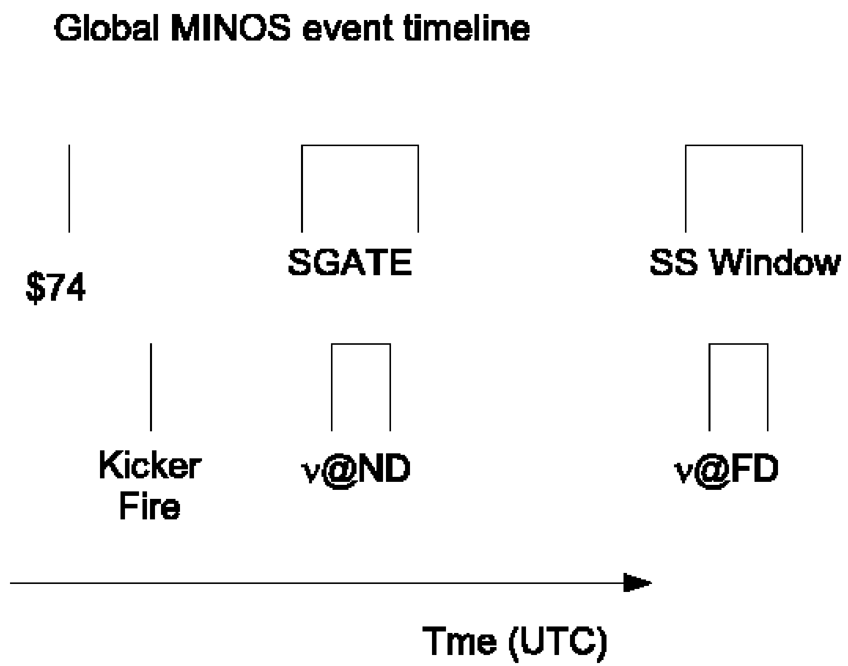
- Could make first measurement on θ_{13} or improve current best limit set by CHOOZ

Selecting Charged Current Interactions: Input PID Variables , Far MC



Event catching: Timing and Triggering

- The elements of the timing system are as follows:
  - $74 signal from Main Injector – tells kicker magnet (which extracts protons to NuMI) that it is in the queue to fire (which it does ~220 us later).
  - $74 signal sent to clock controller at ND & a spill gate (SGATE) window is opened (in hardware) for 13us around the time neutrinos hit the ND (with an offset of –1.5us)
  - SpillServer process at FD informed when most recent spill occurred.
  - FD trigger farm queries SpillServer process every second. If a spill signal has been received and the Spill Trigger is enabled, the DAQ reads out 100us of previously buffered data around the predicted time that the neutrinos should have hit the FD



Event generator

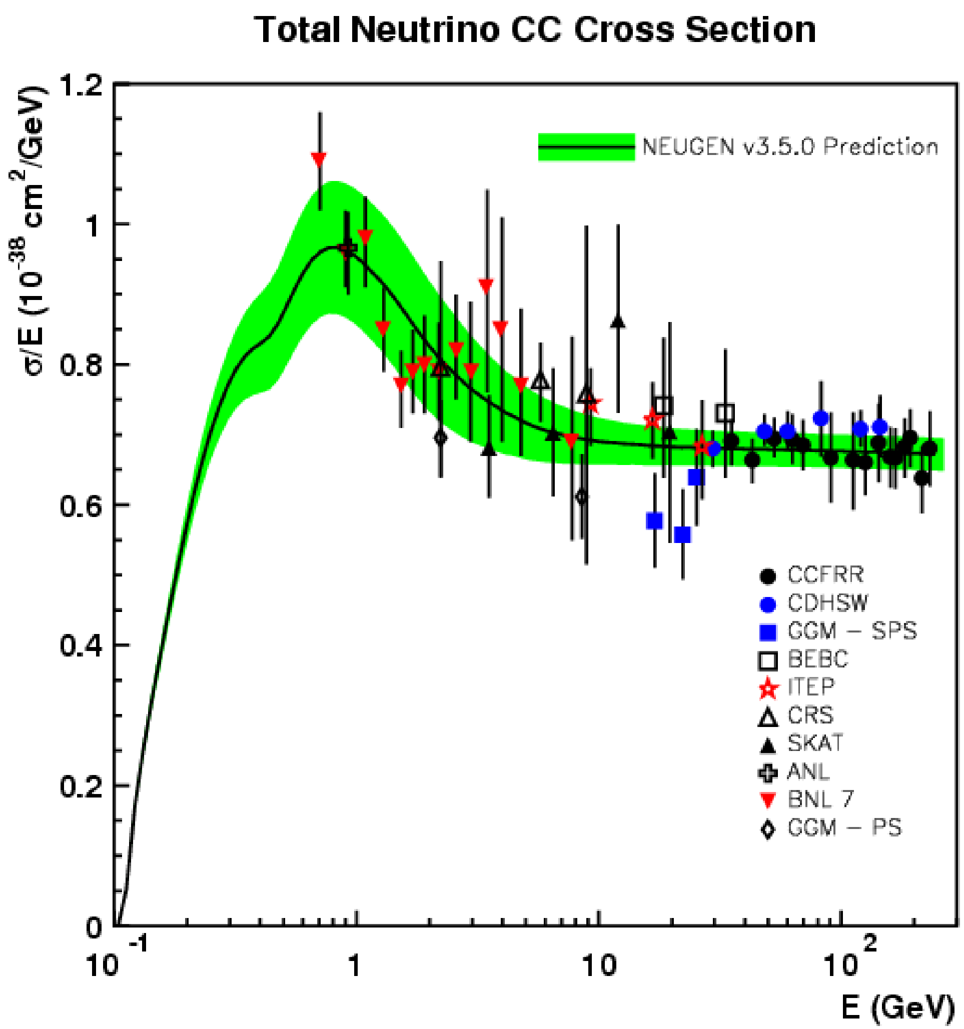
Neutrino-nucleus interactions were generated using the NEUGEN3 neutrino event generator (H. Gallagher, Nucl.Phys.Proc.Suppl. **112**: 188-194, 2002)

Quasi-Elastic: dipole parametrization of form factors with ma=0.99 GeV/c^2 (BBBA05 Bradford et al. Nucl.Phys.Proc.Suppl.159:127-132,2006)

Resonance Production:
Rein-Seghal model for W<1.7 GeV/c^2.
(Annals Phys. **133**: 79, 1981)

DIS: Bodek-Yang modified LO model.
For W<1.7 GeV tuned to electron and neutrino data in the resonance / DIS overlap region. (Bodek-Yang, Nucl. Phys. Proc. Suppl. **139**: 113-118, 2005 and H. Gallagher, NuINT05 Proceedings)

Coherent Production:
Rein-Seghal (Nucl. Phys. B **223**: 29, 1983)



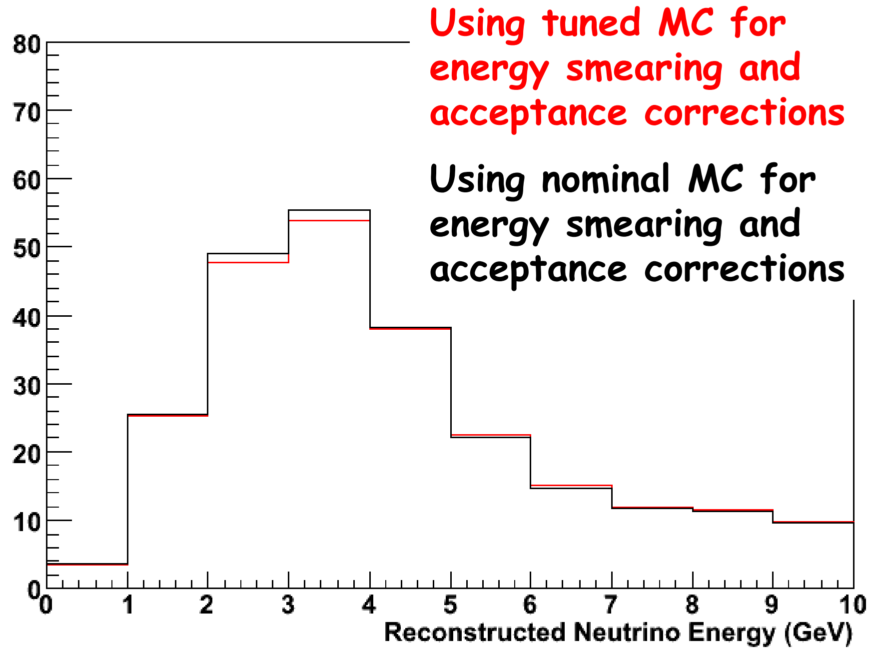
NuMI Alignment

Align the center of ν beam to the Far Detector in the Soudan mine. Goal is within 12 m.

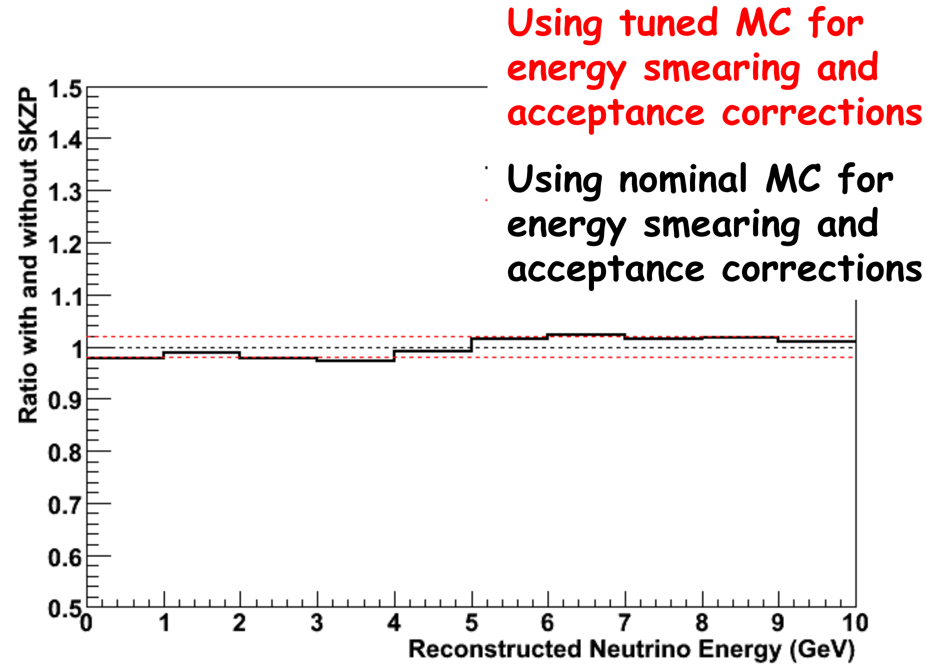
- Fermilab to Soudan surface done using GPS
  - determined vector to 0.01 m horiz., 0.06 m vertical
- Soudan surface to 27th level
  - 0.7 m per coordinate
- Fermilab surface to underground
  - gyrotheodolite with 0.015 mrad precision
  - 11 m at Soudan
- Transverse alignment of baffle, target and horn at 0.5 mm

Effect of MC tuning on the measurement

Far Predicted Spectra using the Beam Matrix and with/without hadron production tuning



Ratio of Far Prediction using the Beam Matrix and with/without hadron production tuning



- Using Beam Matrix Method, hadron production tuning does not affect the Unoscillated prediction (obtained from the ND data) by more than 1-2%.
- However, its use improves the MC (make it more similar to the data) and therefore uncertainties due to energy smearing-unsmearing and acceptance become smaller.

Predicted numbers of FD events

Ratios to Beam Matrix prediction

Method	0-30 GeV	0-3 GeV	3-6 GeV	6-10 GeV	10-30 GeV	30-200 GeV
Beam Matrix	1.000	1.000	1.000	1.000	1.000	1.000
NDFit	1.004	1.019	0.996	1.019	0.994	0.978
2DFit	1.006	1.044	0.983	1.000	1.009	0.971
Far/Near	0.995	1.013	0.979	1.003	0.996	0.992

FD predictions - Ratio to Beam Matrix

RunI spectrum

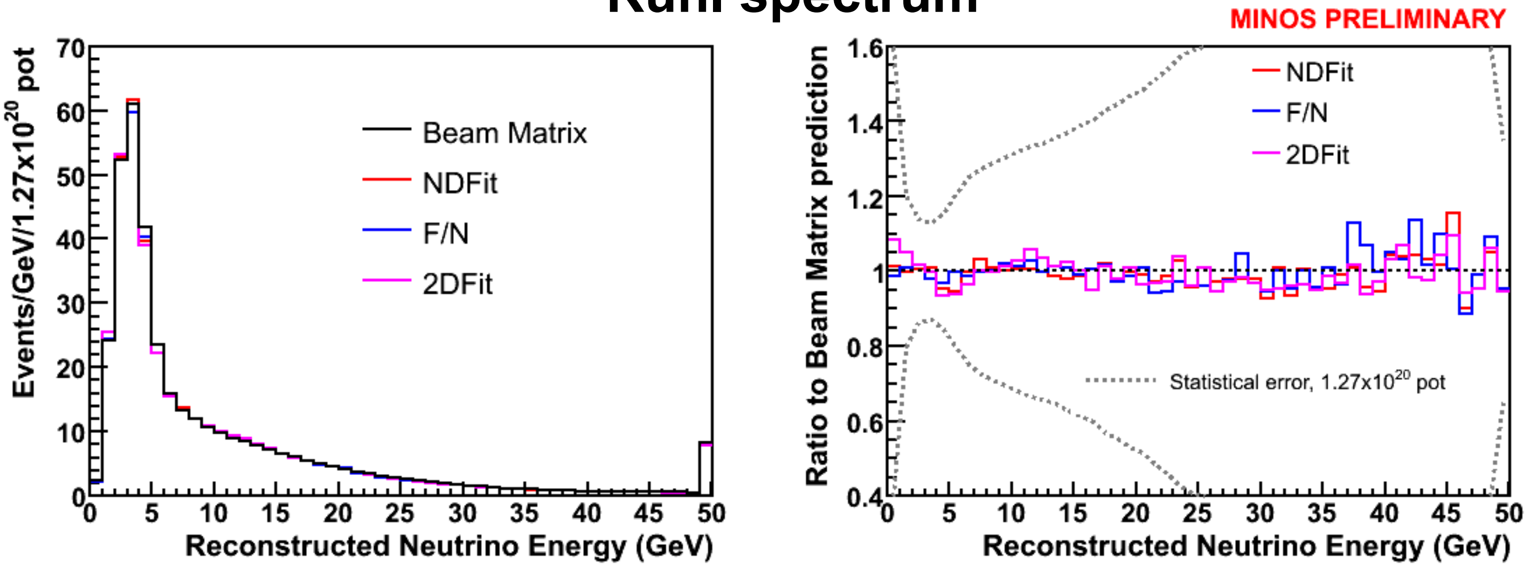
Method	0-30 GeV	0-3 GeV	3-6 GeV	6-10 GeV	10-30 GeV	30-200 GeV
Beam Matrix	1.000	1.000	1.000	1.000	1.000	1.000
NDFit	0.992	1.005	0.979	1.010	0.990	0.976
2DFit	0.994	1.029	0.967	0.992	1.004	0.968
Far/Near	0.994	1.014	0.979	1.000	0.995	0.988

RunIIa spectrum

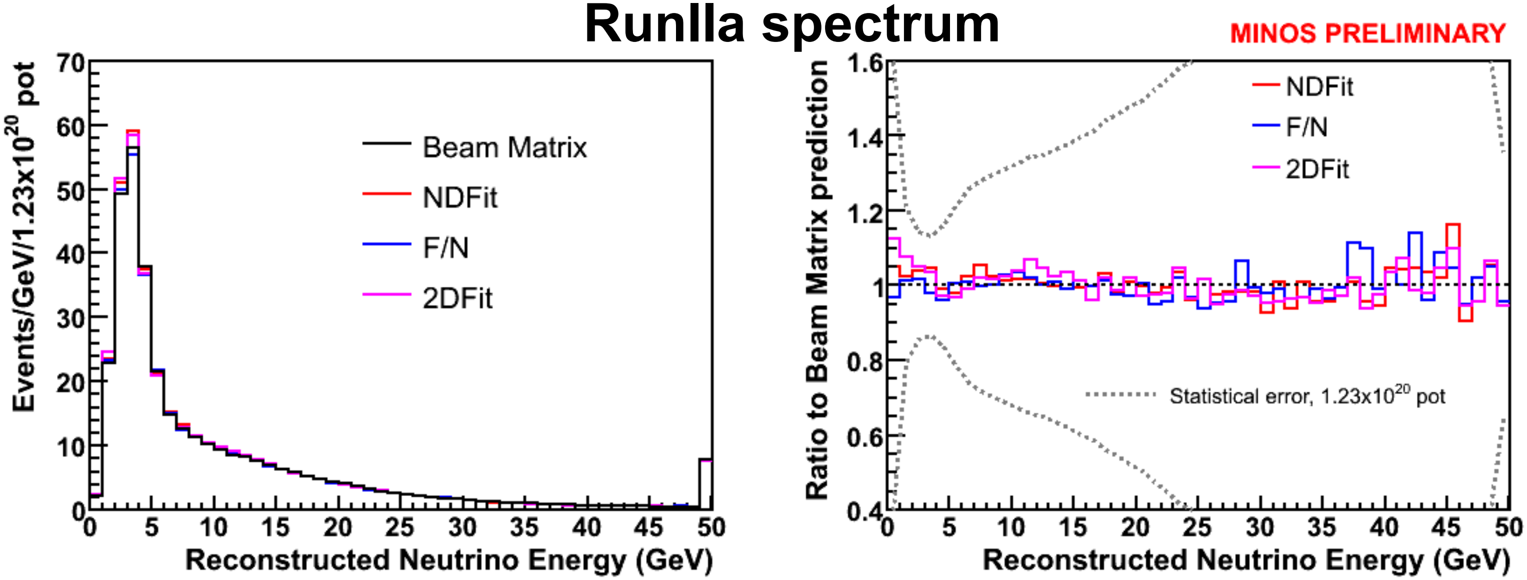
Method	0-30 GeV	0-3 GeV	3-6 GeV	6-10 GeV	10-30 GeV	30-200 GeV
Beam Matrix	1.000	1.000	1.000	1.000	1.000	1.000
NDFit	1.017	1.034	1.014	1.028	0.999	0.980
2DFit	1.019	1.059	1.001	1.010	1.014	0.972
Far/Near	0.996	1.013	0.978	1.008	0.999	0.992

FD predicted spectra - pre/post shutdown

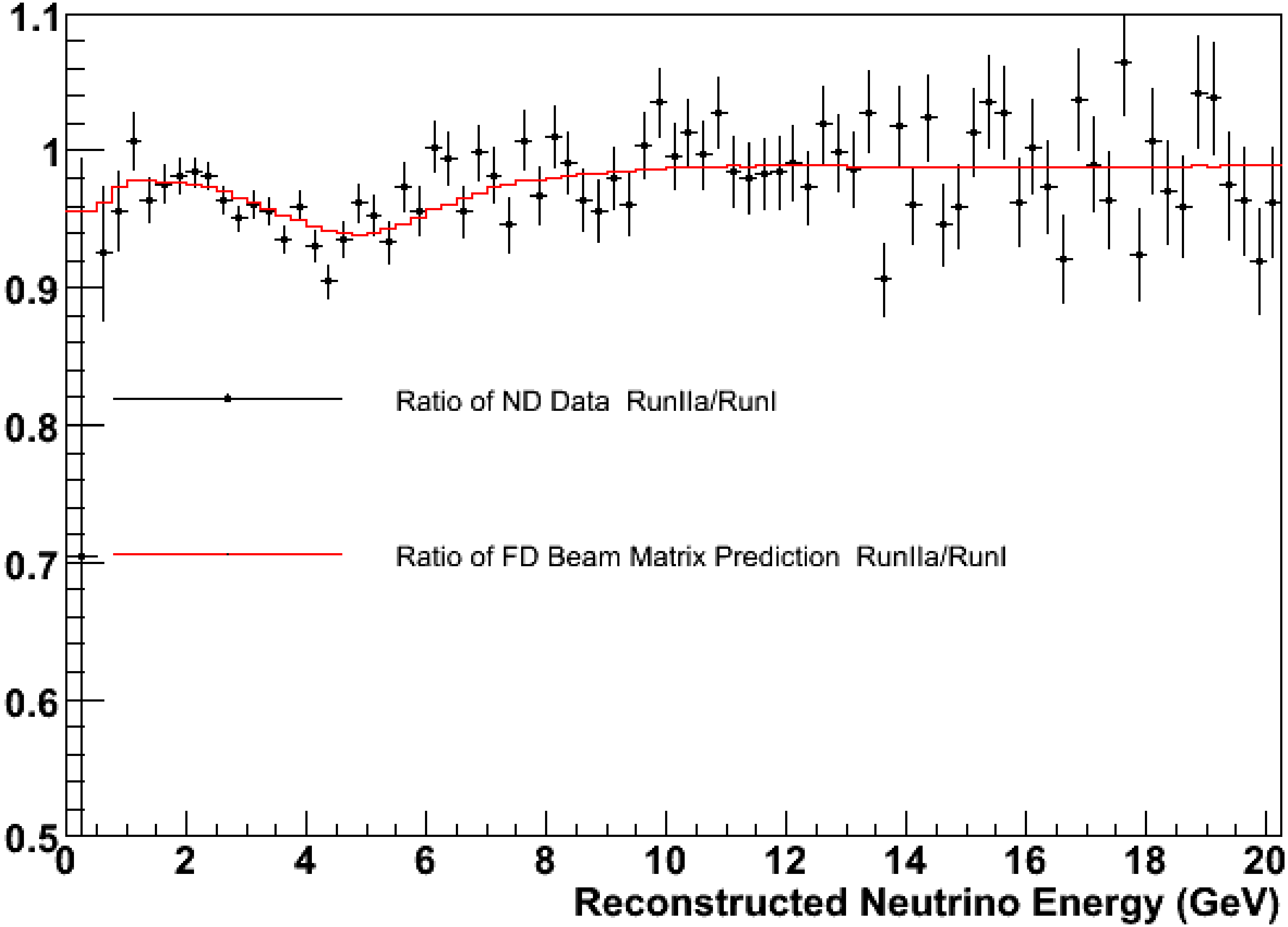
RunI spectrum



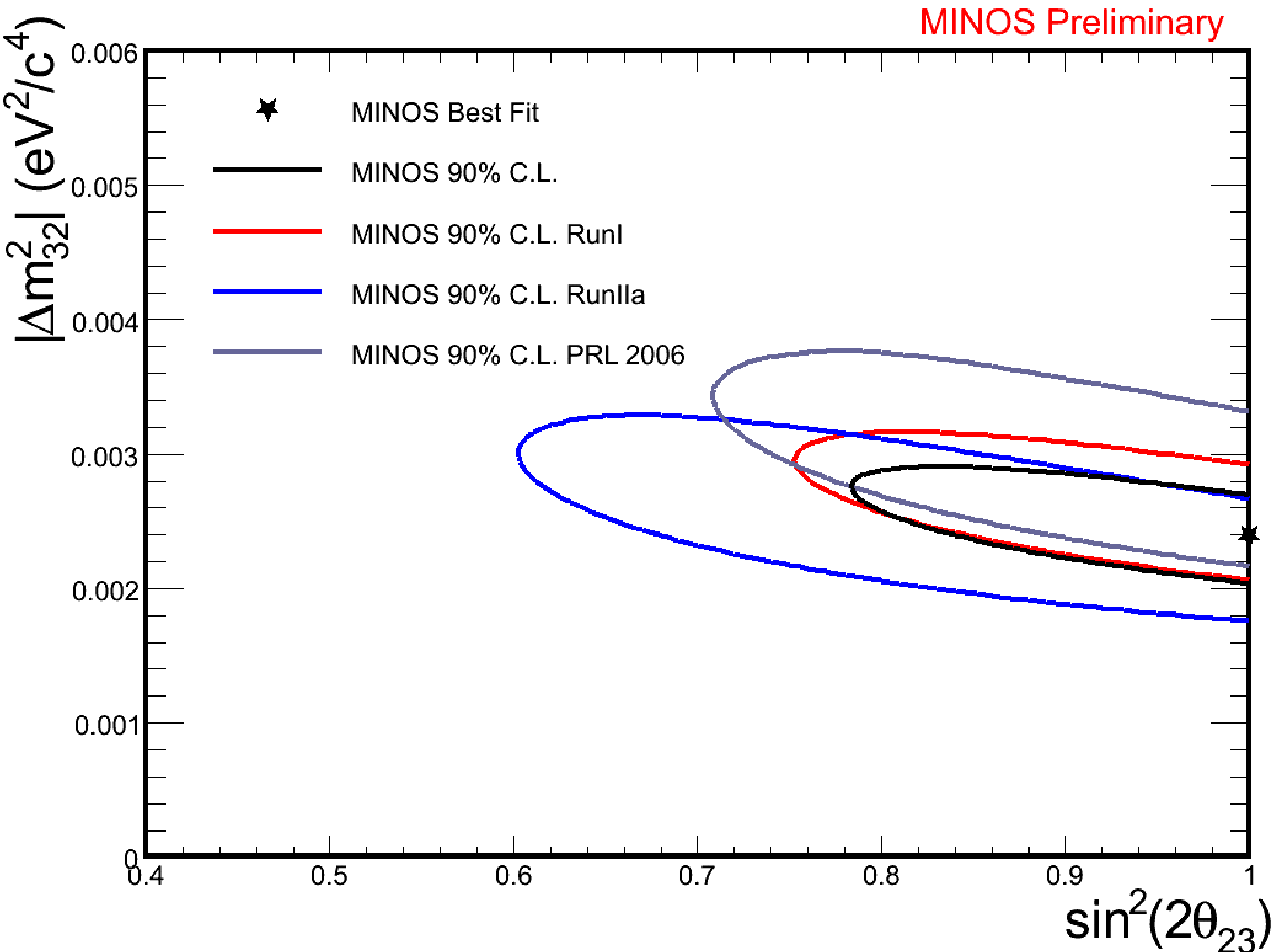
RunIIa spectrum



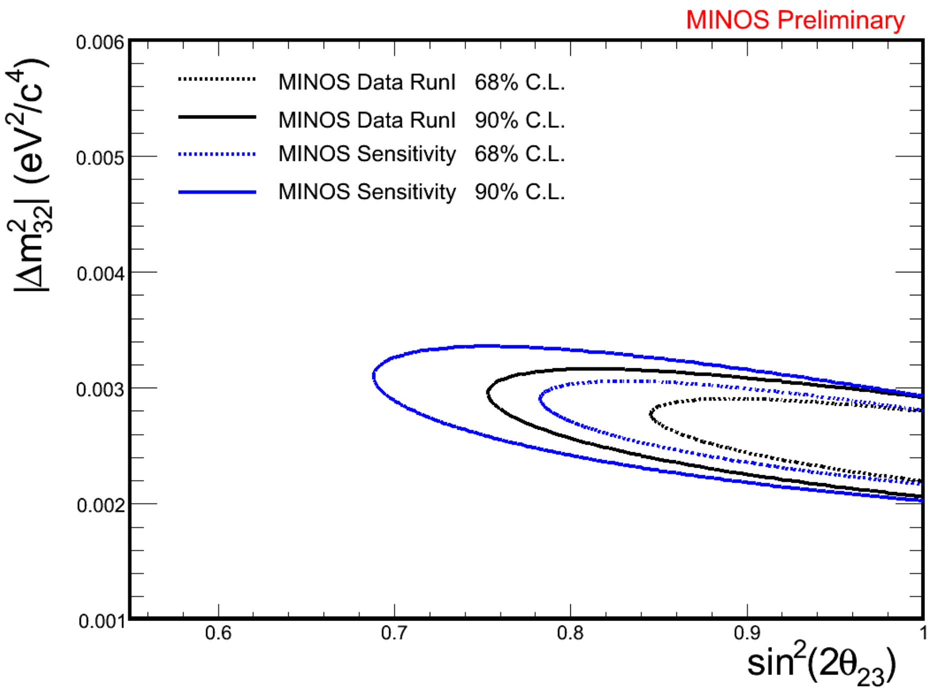
Beam Matrix Prediction & Near Detector Data : RunI/RunIIa

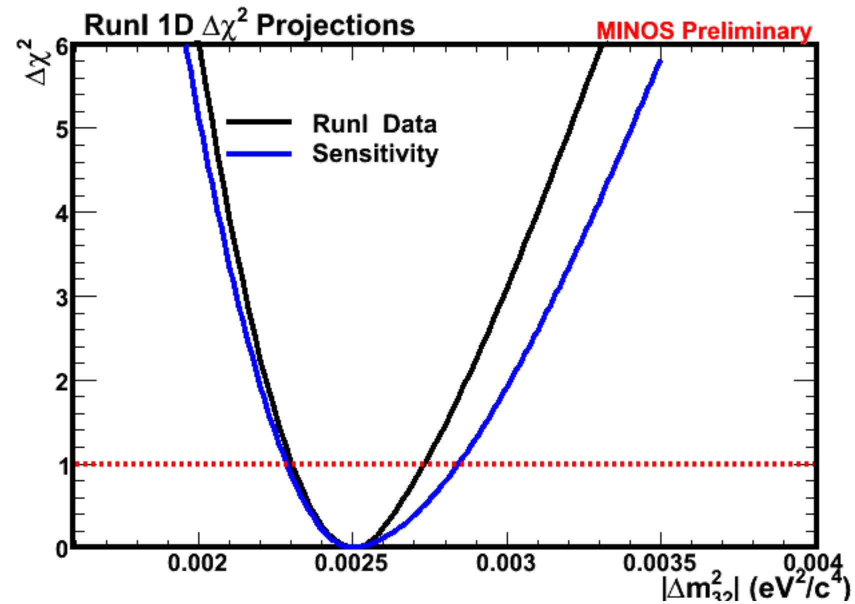


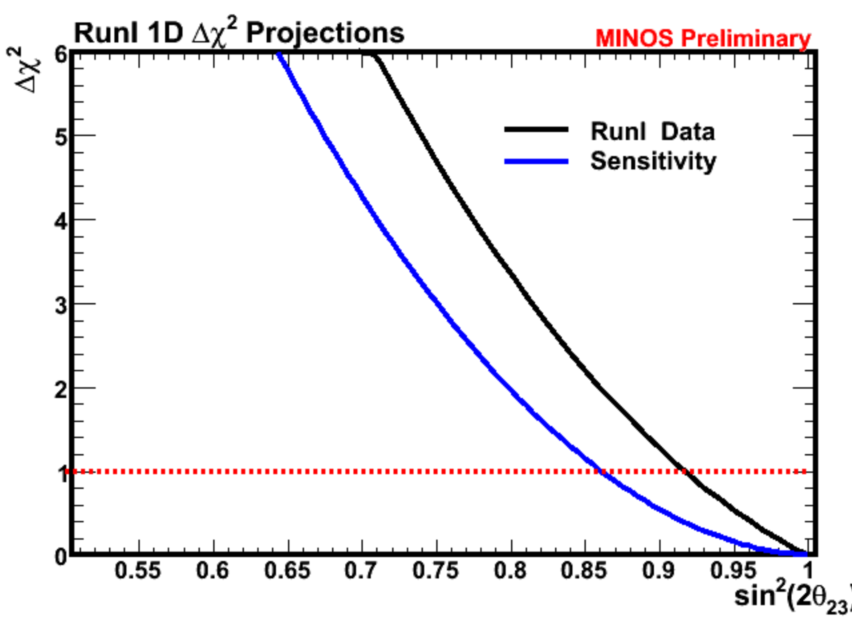
MINOS Data Samples



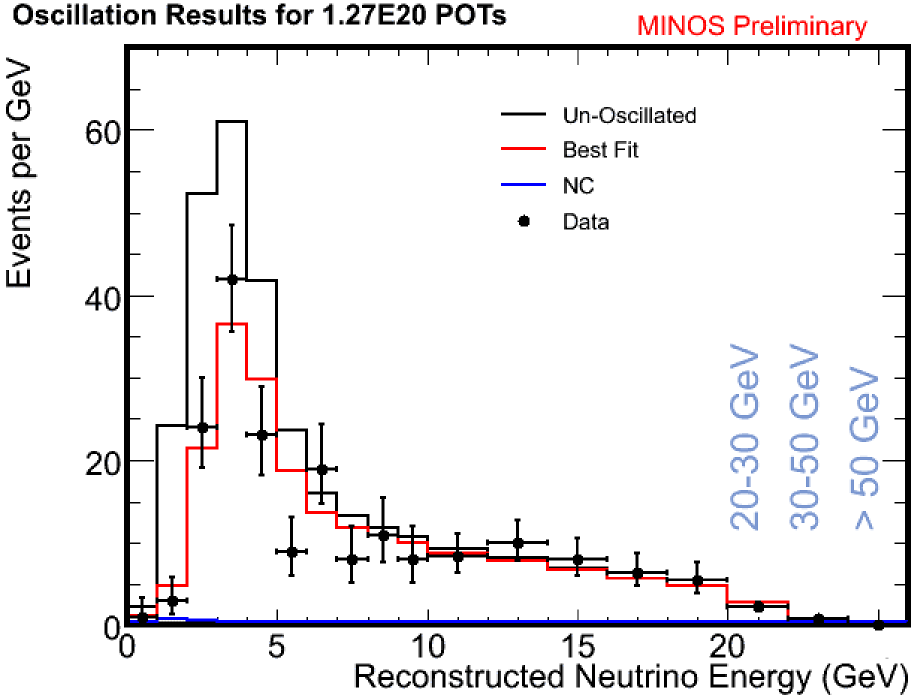
Beam Matrix Results RunI

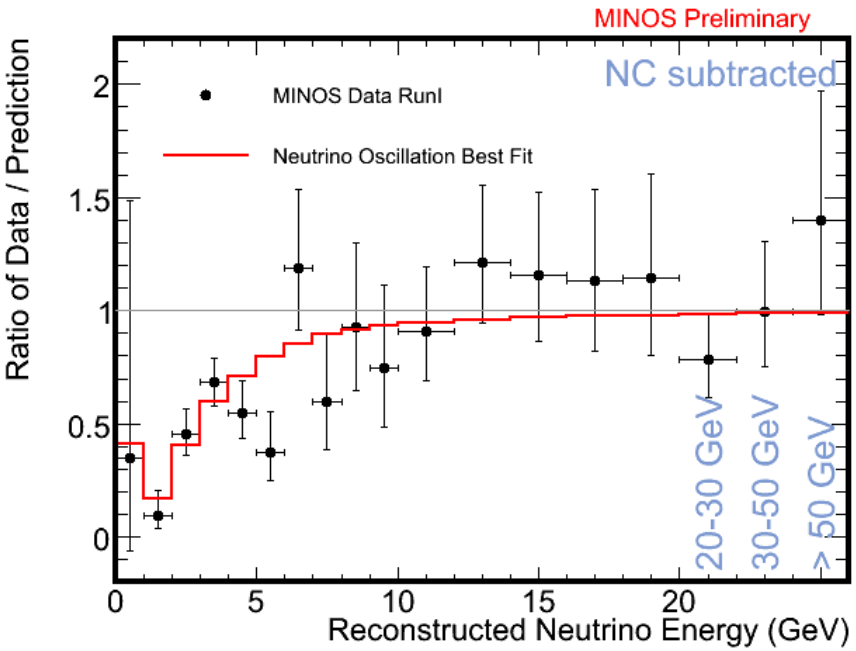




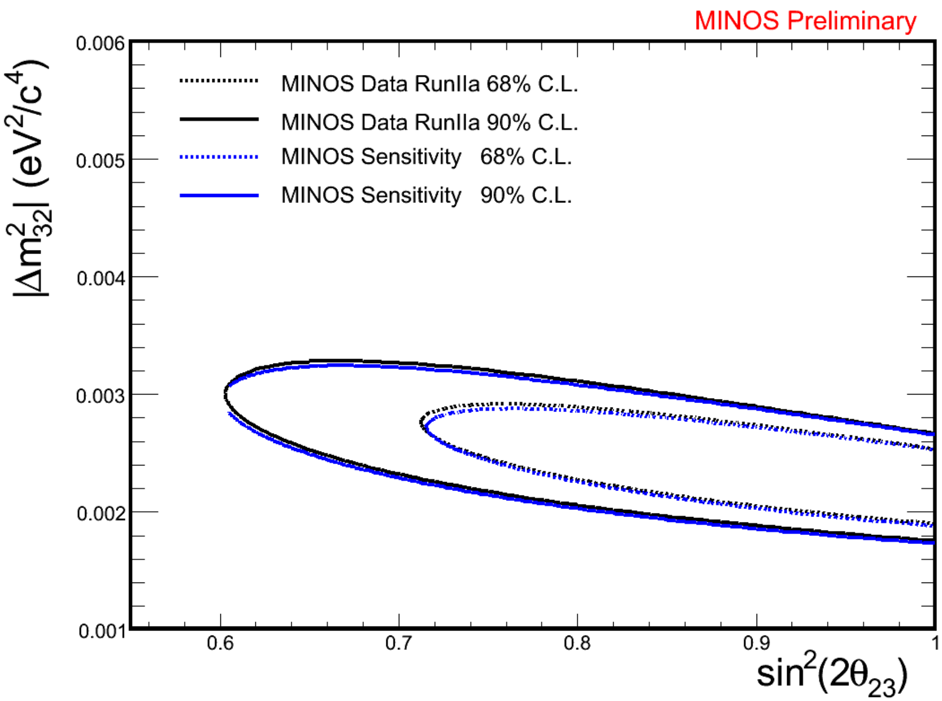


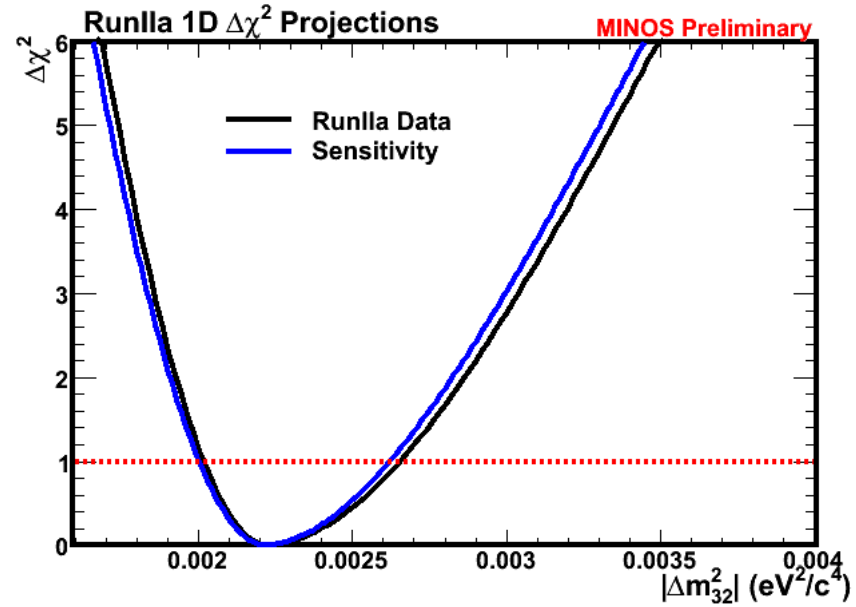
Beam Matrix Results RunI

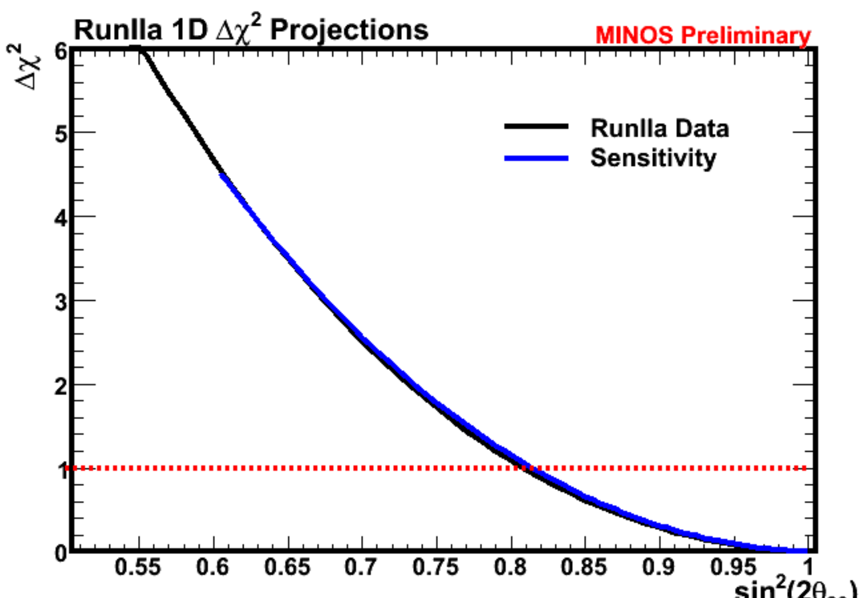




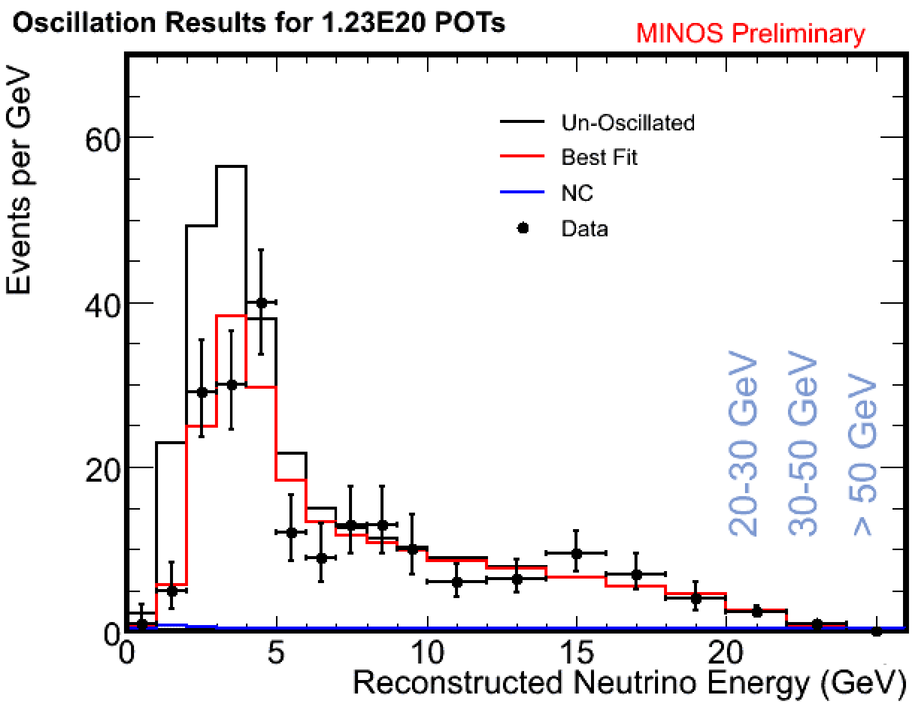
Beam Matrix Results RunIIa

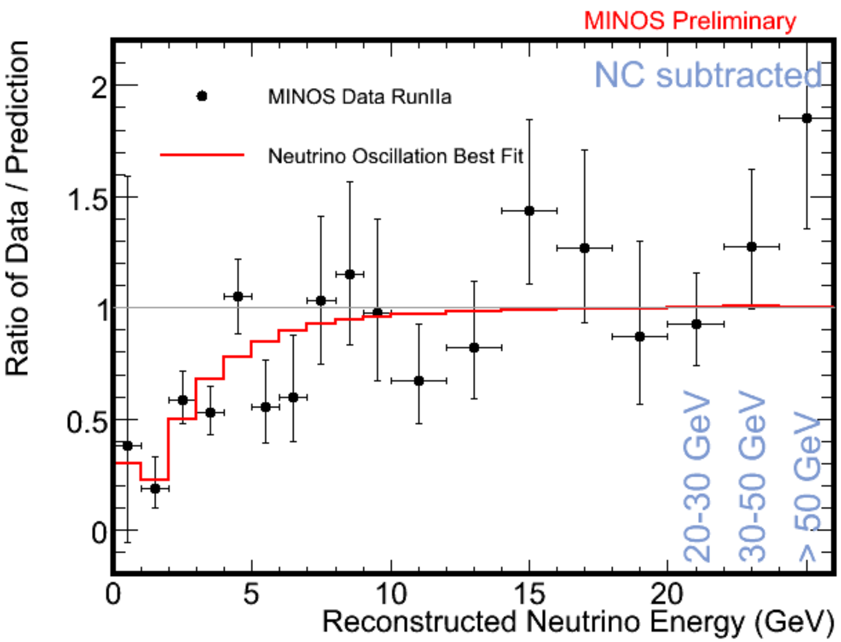






Beam Matrix Results RunIIa





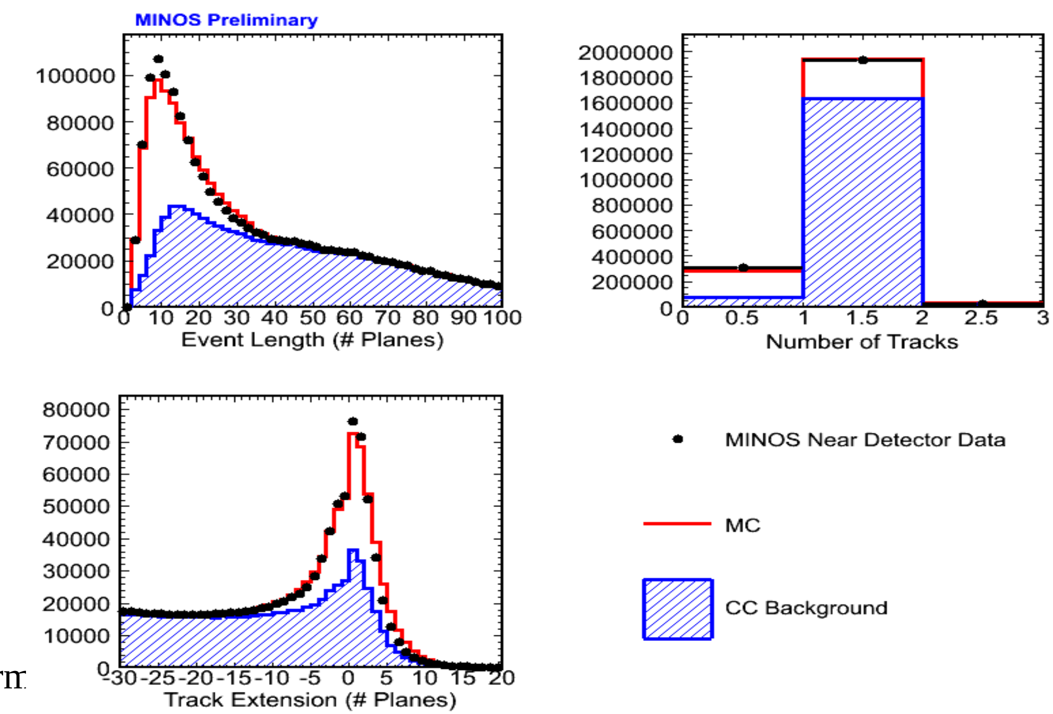
Neutral Current Analysis : Near Detector NC-like Spectrum

- *Goal is a NC spectrum measurement in the FD which is* **Sensitive to $\nu_\mu \rightarrow \nu_{sterile}$, ν decay signatures…**

  -First step of this analysis is a measurement of the NC spectrum in the Near Detector.

  - Second step is the use of similar techniques to the CC analysis to extrapolate measured spectrum to the Far Detector and compare with the data

Use simple cuts to select NC events with high (93%) efficiency (CC contamination ~50%)



The agreement of NC Selection Variables between Data and MC is good.

Neutral Current Analysis : Near Detector NC-like Spectrum

• **Unlike the Far Detector our Near Detector "sees" a lot of neutrinos per beam spill (event overlapping).**

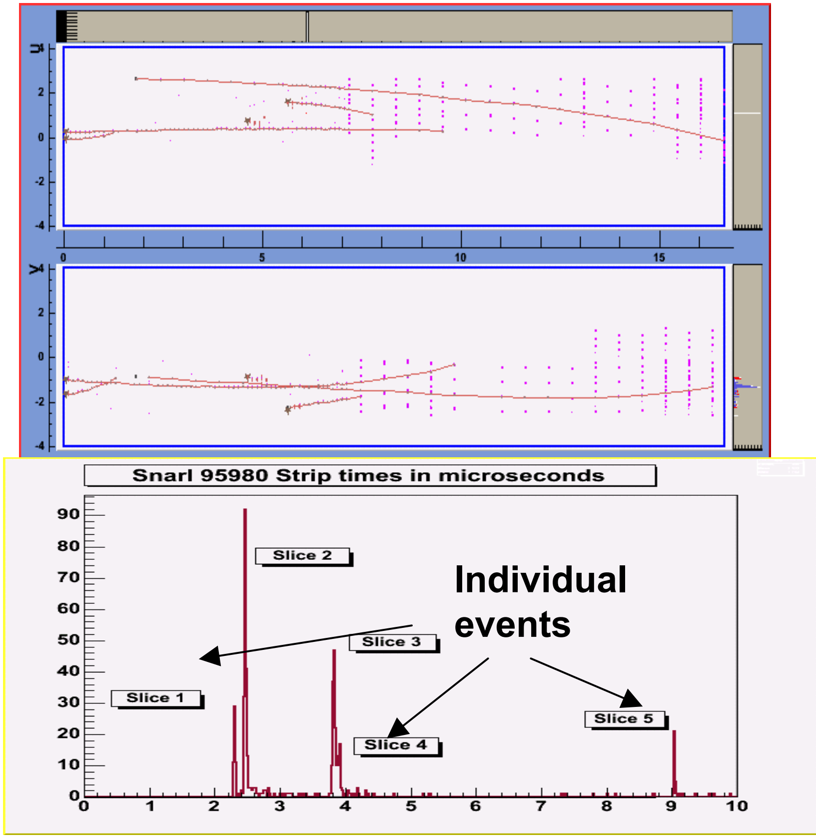
• To ensure that event overlapping is not affecting the NC-like spectrum we reconstruct we developed two independent methods to obtain clean samples of events for data/MC comparisons in the Near Detector :

> **-Both are designed to reject events that overlap in time and space and/or are not well-reconstructed:**

1) High multiplicity selection: **Uses timing & topological cuts (selects 860K NC-like events for 1.23e20 pot)**

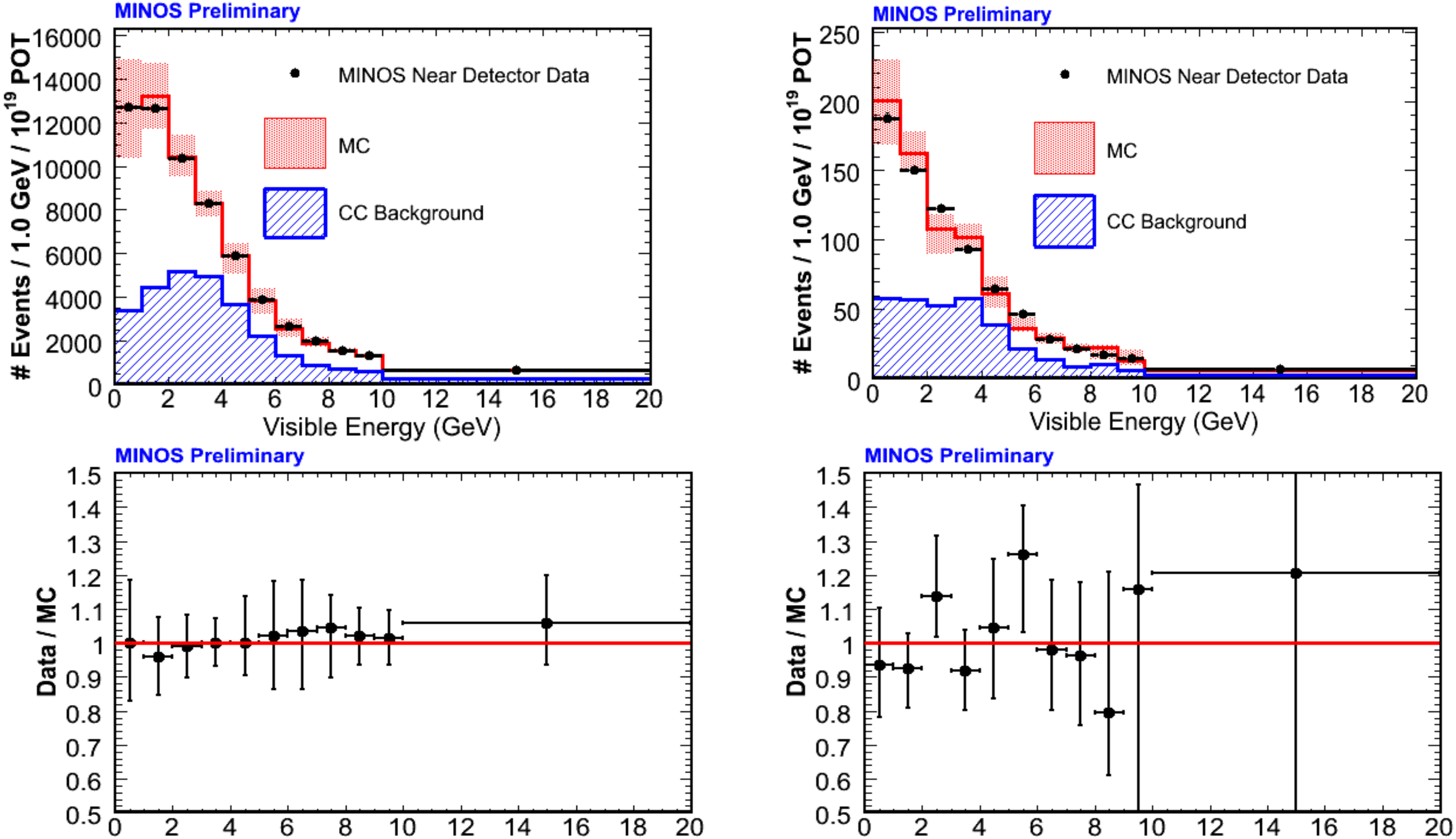
2) Low multiplicity selection: **Use only spills with 1 or 2 reconstructed events (selects 10472 NC-like events for 1.23e20 pot)**

One near detector spill



Time (us)

Neutral Current Analysis : Near Detector NC-like Spectrum cont'd



- MC error band includes contributions from beam, cross-section and energy scale uncertainties
- Both methods (high and low multiplicity data cleaning) give results consistent with each other and with expectations.